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(54) Abstract Title

A quantum dot photon source

(57) A photon source 21 can emit single photons, or pulses of N photons, at predetermined intervals. The source comprises at least one quantum dot 35 having two energy levels which can be respectively populated by an electron and a hole, there being supply means which can supply a predetermined number of caters to one of the energy levels to allow recombination of a predetermined number of carriers in the quantum dot so that at least one photon is emitted. The quantum dot(s) are encapsulated between two layers having a different lattice constant to the quantum dot(s) and may formed in a cavity between two mirrors 51,53, e.g. Bragg mirrors, one of which may be partially reflective to allow the photon(s) to enter an optical fibre. The supply means may be a laser beam, pulsed or continuous, to excite carriers into the energy levels, and may have means to modulate the transition energy of the quantum dot(s), e.g. by applying an AC voltage thereacross. In the case of pulsed laser excitation, the pulses desirably have a duration less than the relaxation time of the carriers which are excited, and the time between the leading edges of successive pulses is greater than the recombination time of an electron and a hole in the quantum dot. The source may be used in optical quantum cryptography, or for optical imaging, spectroscopy, laser ranging and metrology.

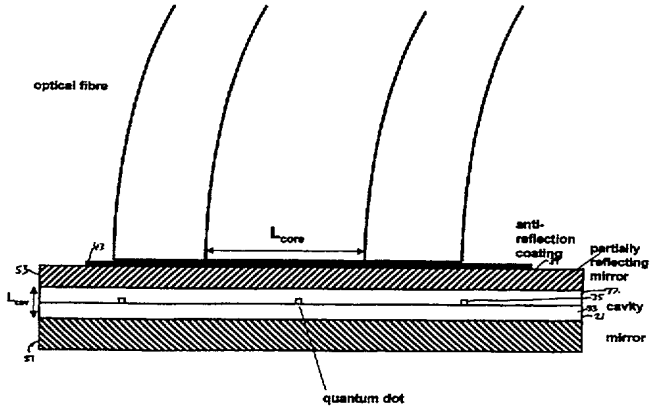

Fig.4

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

GB 2 377 551 A

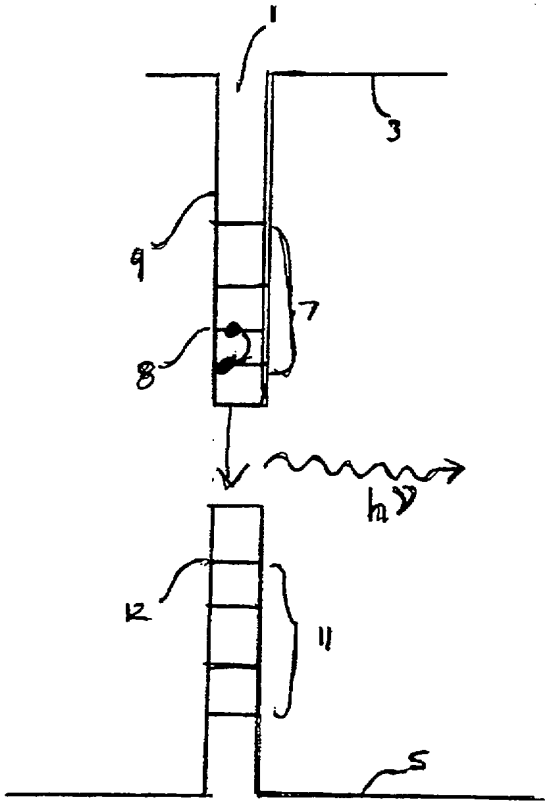

FIGURE 1.

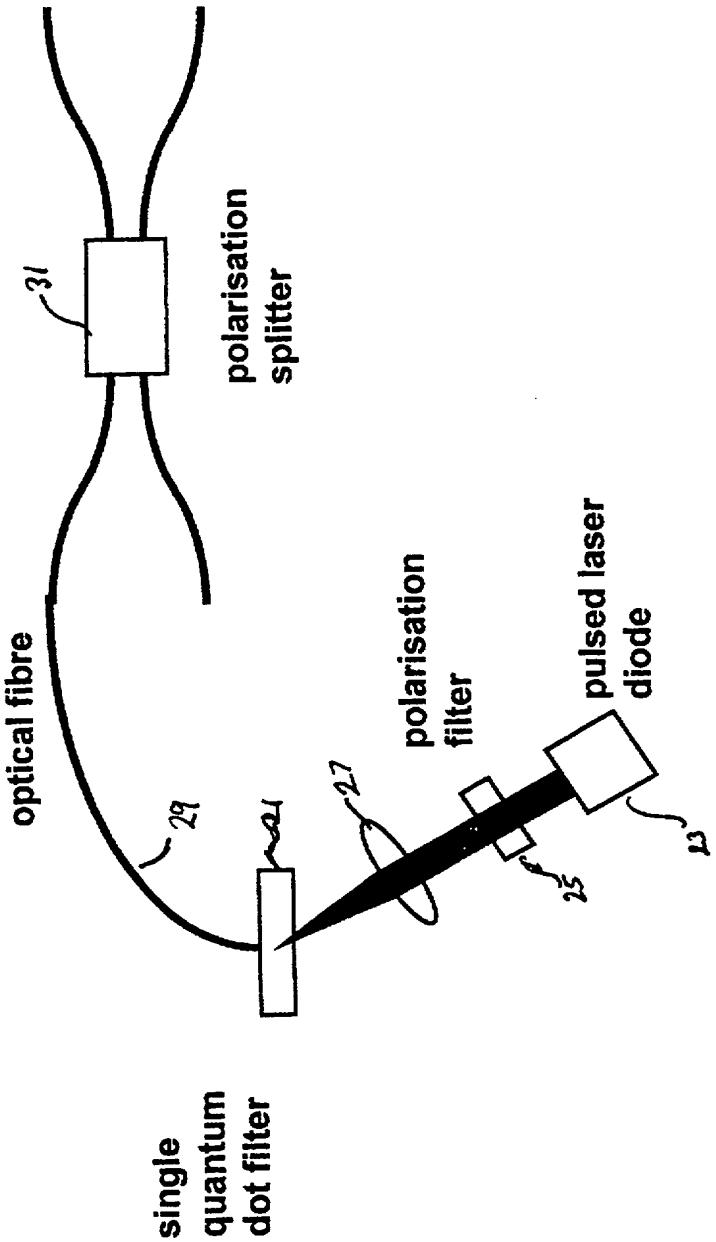
polarisation splitter
31
optical fibre
29
single quantum dot filter
polarisation filter
27
25
pulsed laser diode
23

Fig.2

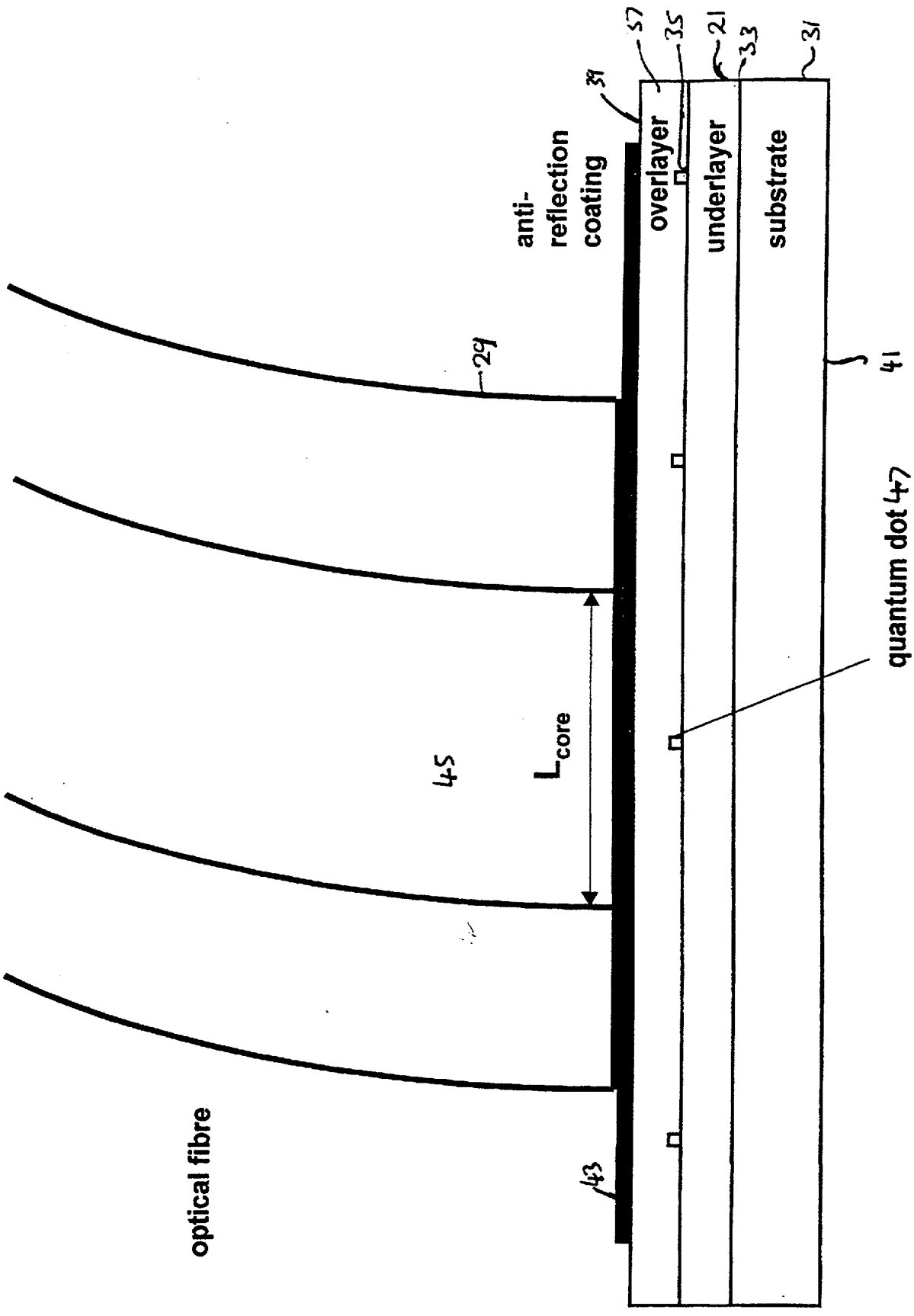
optical fibre
anti-reflection coating
overlayer
underlayer
substrate
quantum dot 47
L_{core}
45
29
39
37
35
21
33
31
41
43

Fig.3

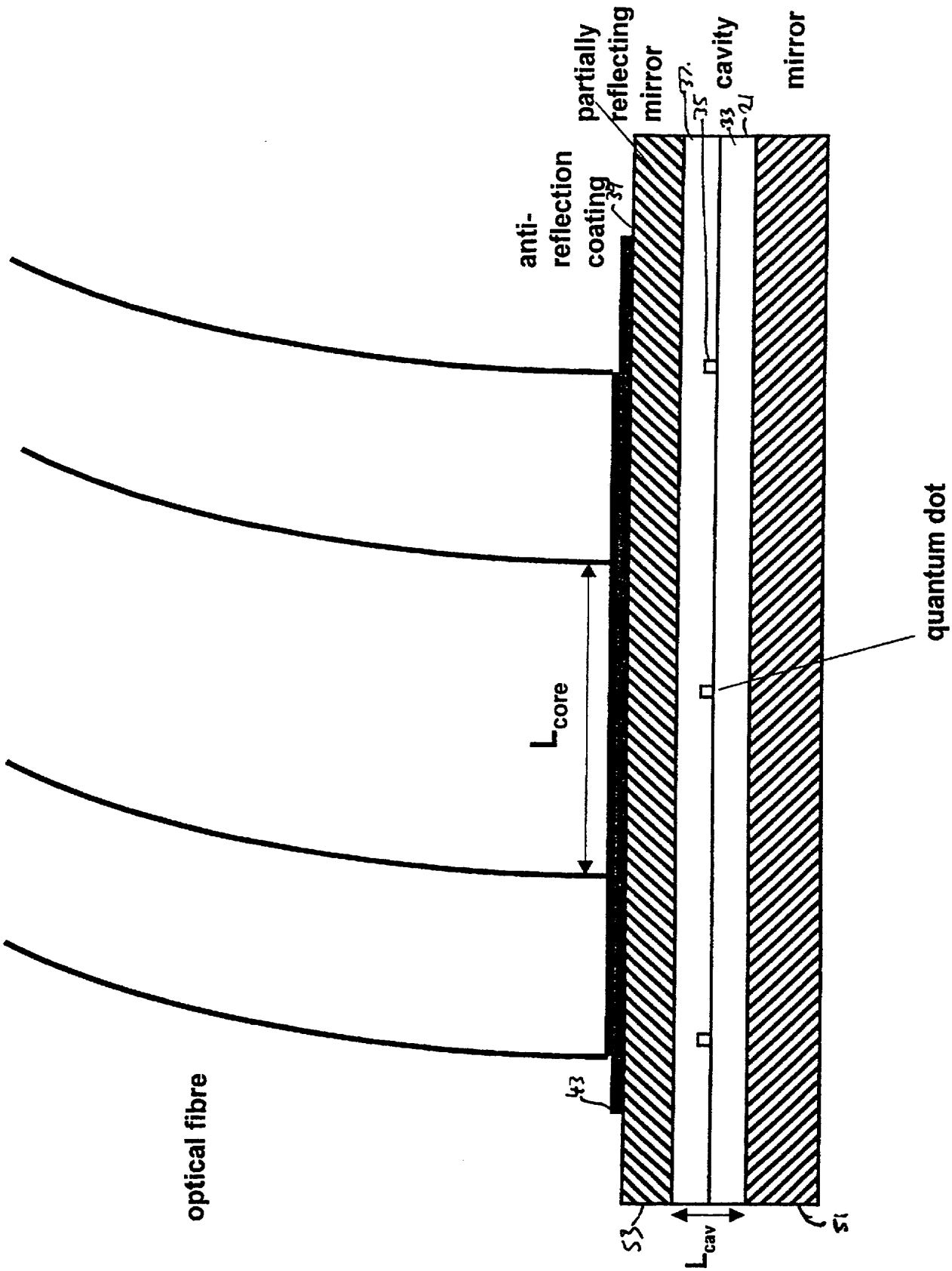
optical fibre
anti-reflection coating
partially reflecting mirror
cavity
mirror
quantum dot
L_{core}
L_{cav}
37
35
33
21
43
53
51

Fig.4

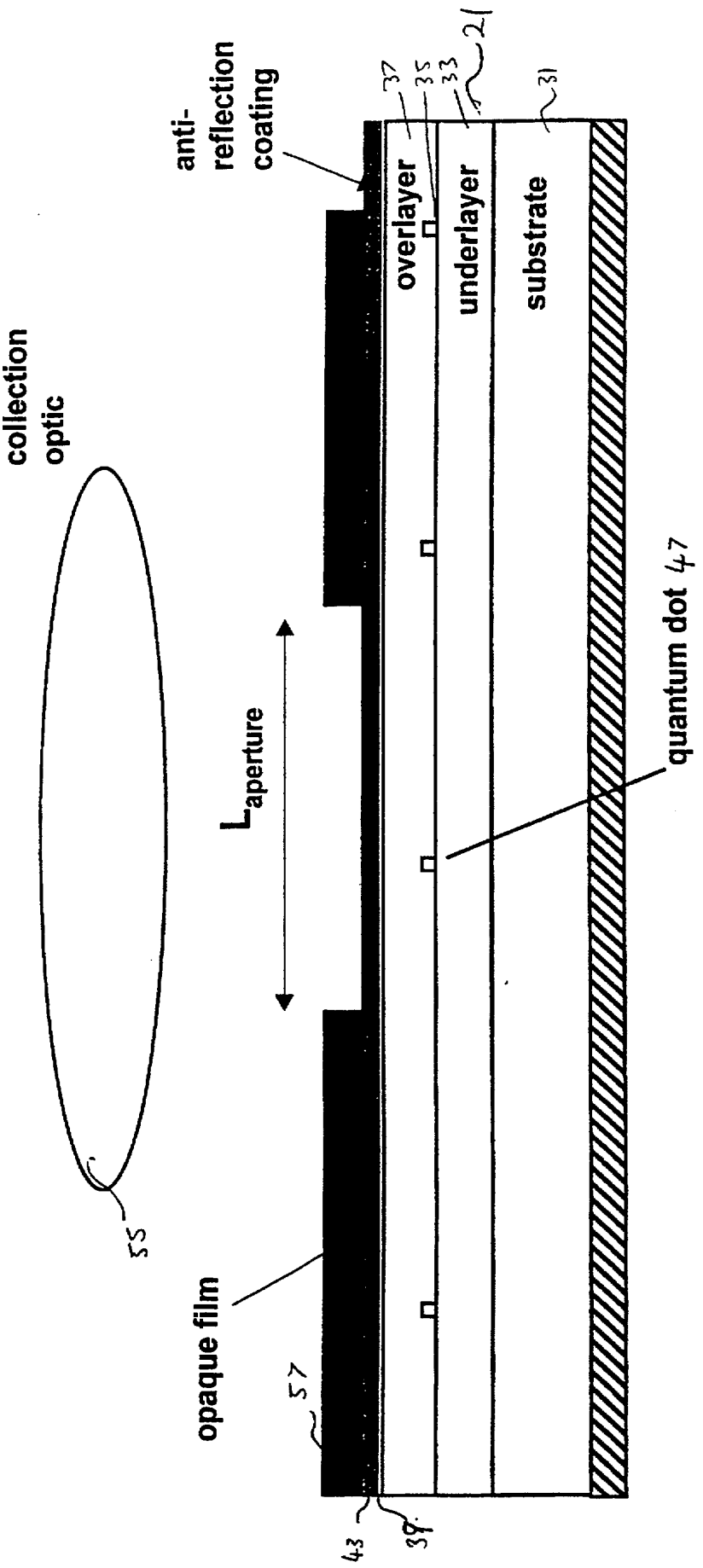
collection optic
anti-reflection coating
overlayer
underlayer
substrate
$L_{aperture}$
quantum dot 47
opaque film
55
57
43
39
37
35
33
21
31

Fig.5

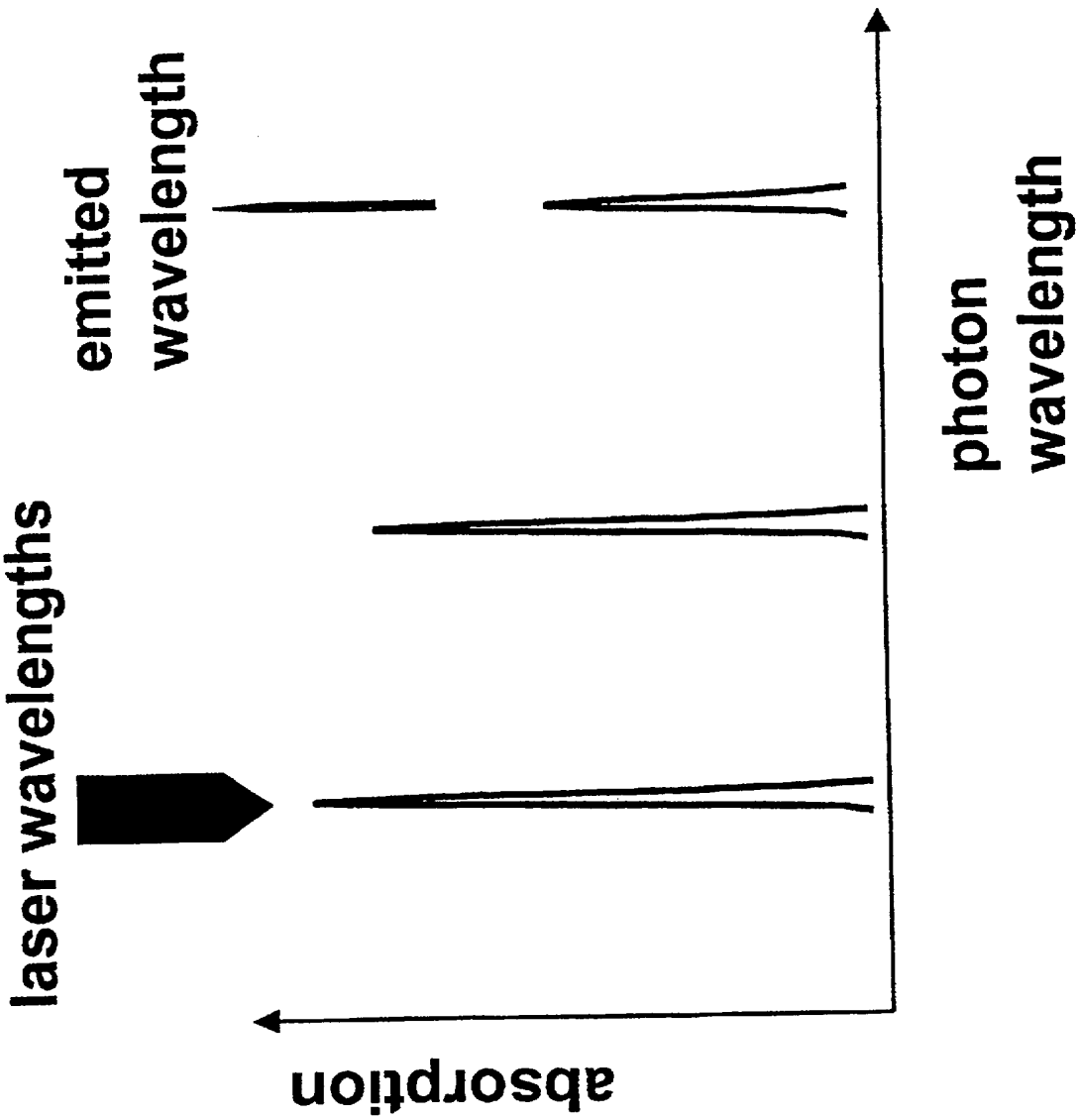
laser wavelengths
emitted wavelength
photon wavelength
absorption

Fig.6

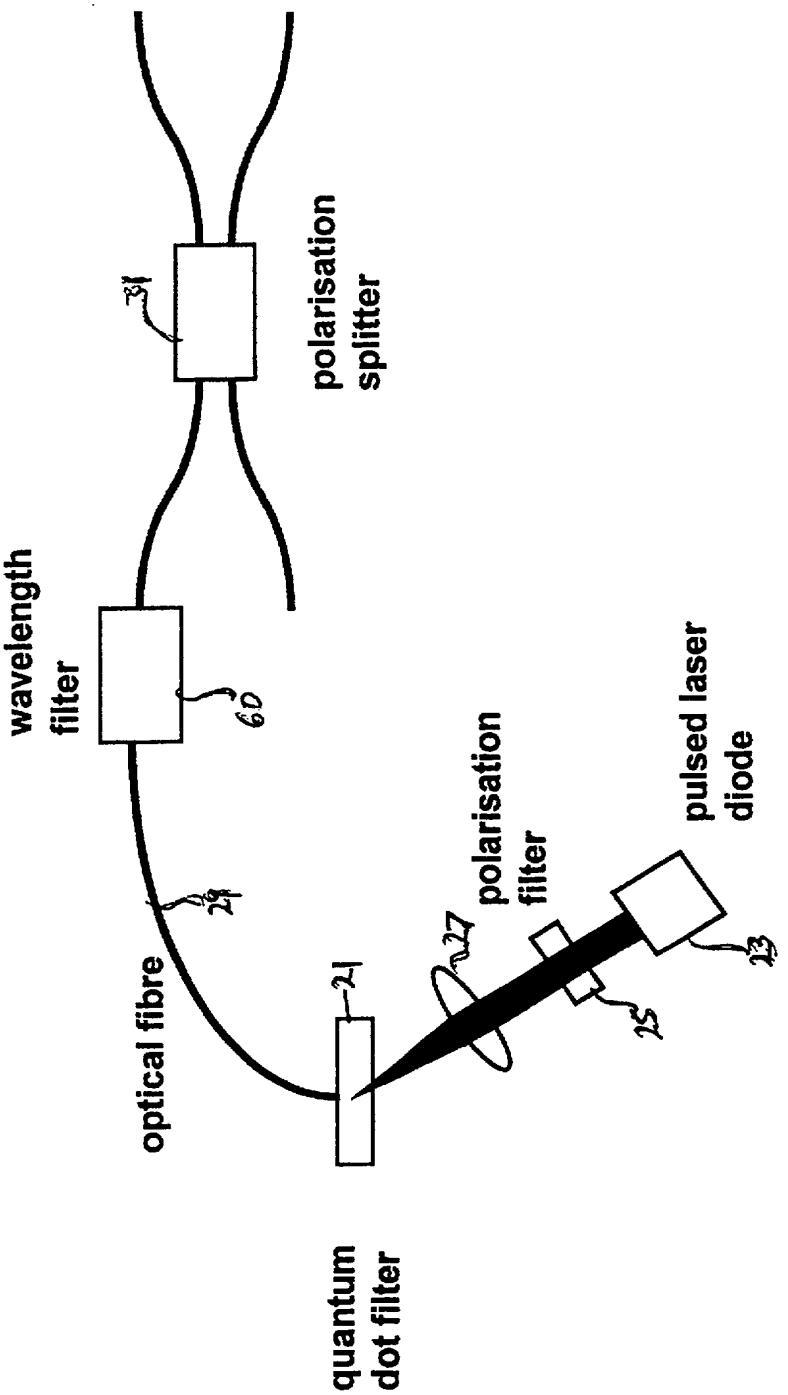
polarisation splitter
31
wavelength filter
60
optical fibre
29
quantum dot filter
21
polarisation filter
27
25
pulsed laser diode
13

Fig.7

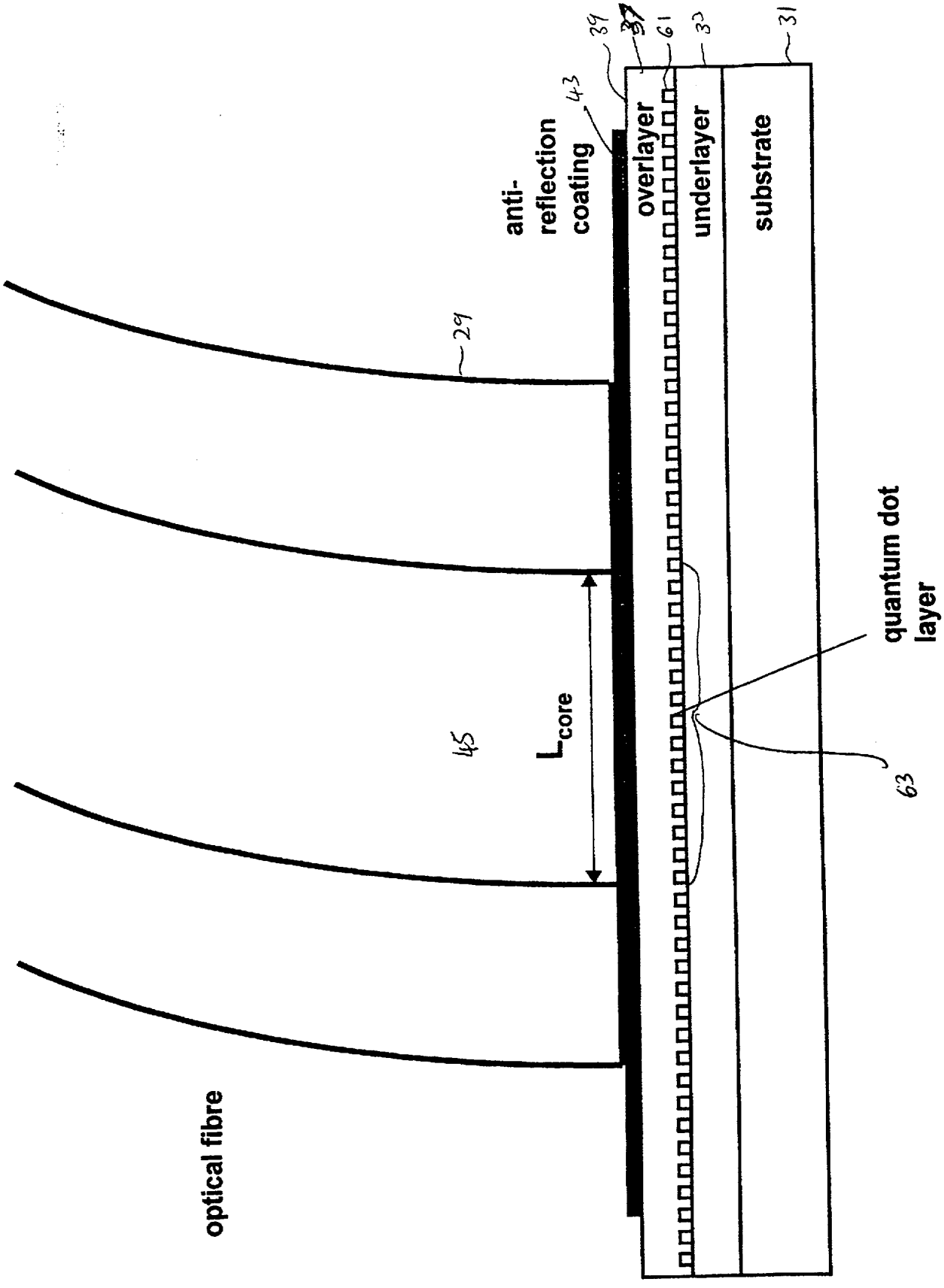
optical fibre
anti-
reflection
coating
overlayer
underlayer
substrate
quantum dot
layer
L_{core}
29
31
33
37
39
43
45
61
63

Fig.8

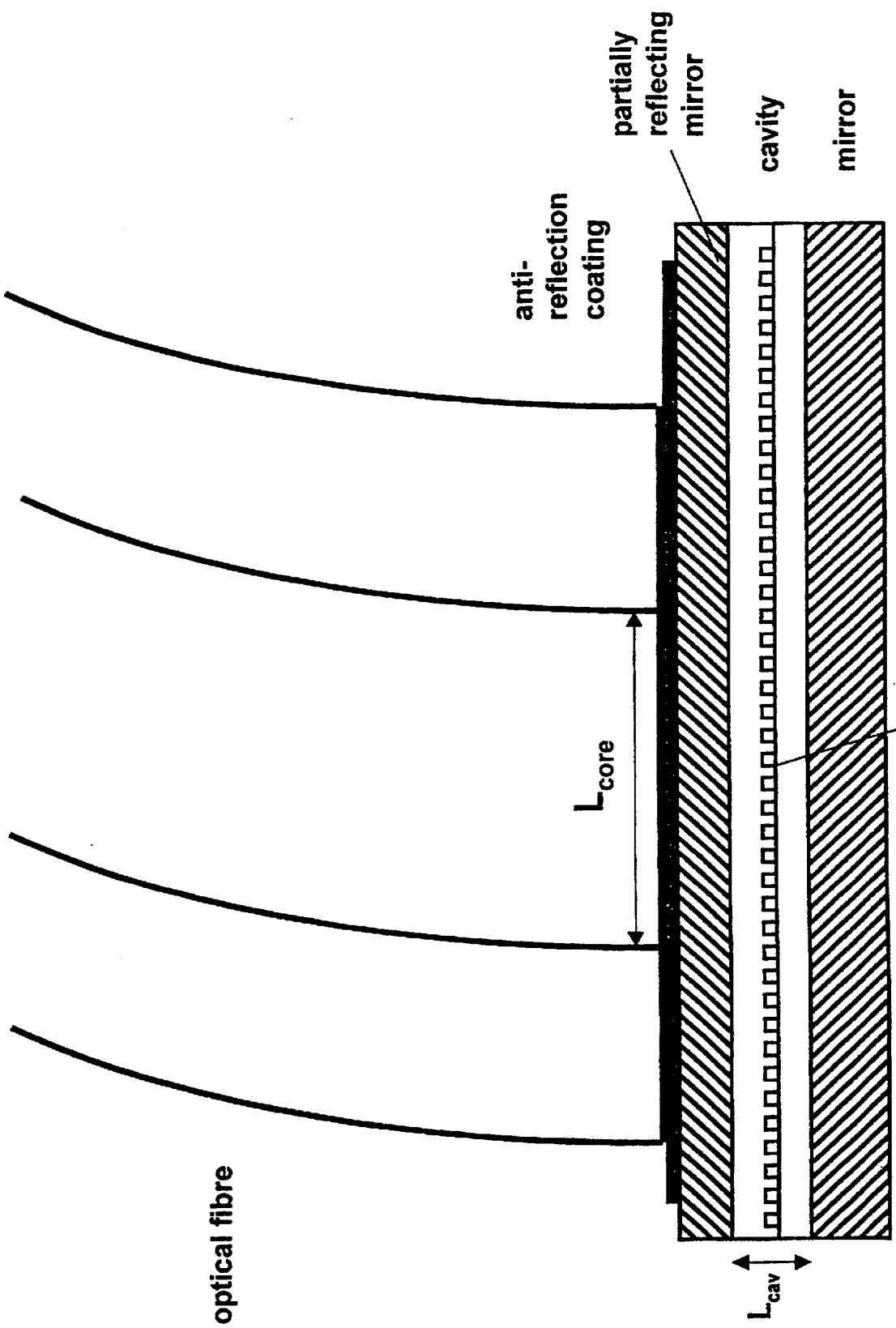
optical fibre
anti-
reflection
coating
partially
reflecting
mirror
cavity
mirror
multiple quantum
dot layer
L_{core}
L_{cav}

Fig.9

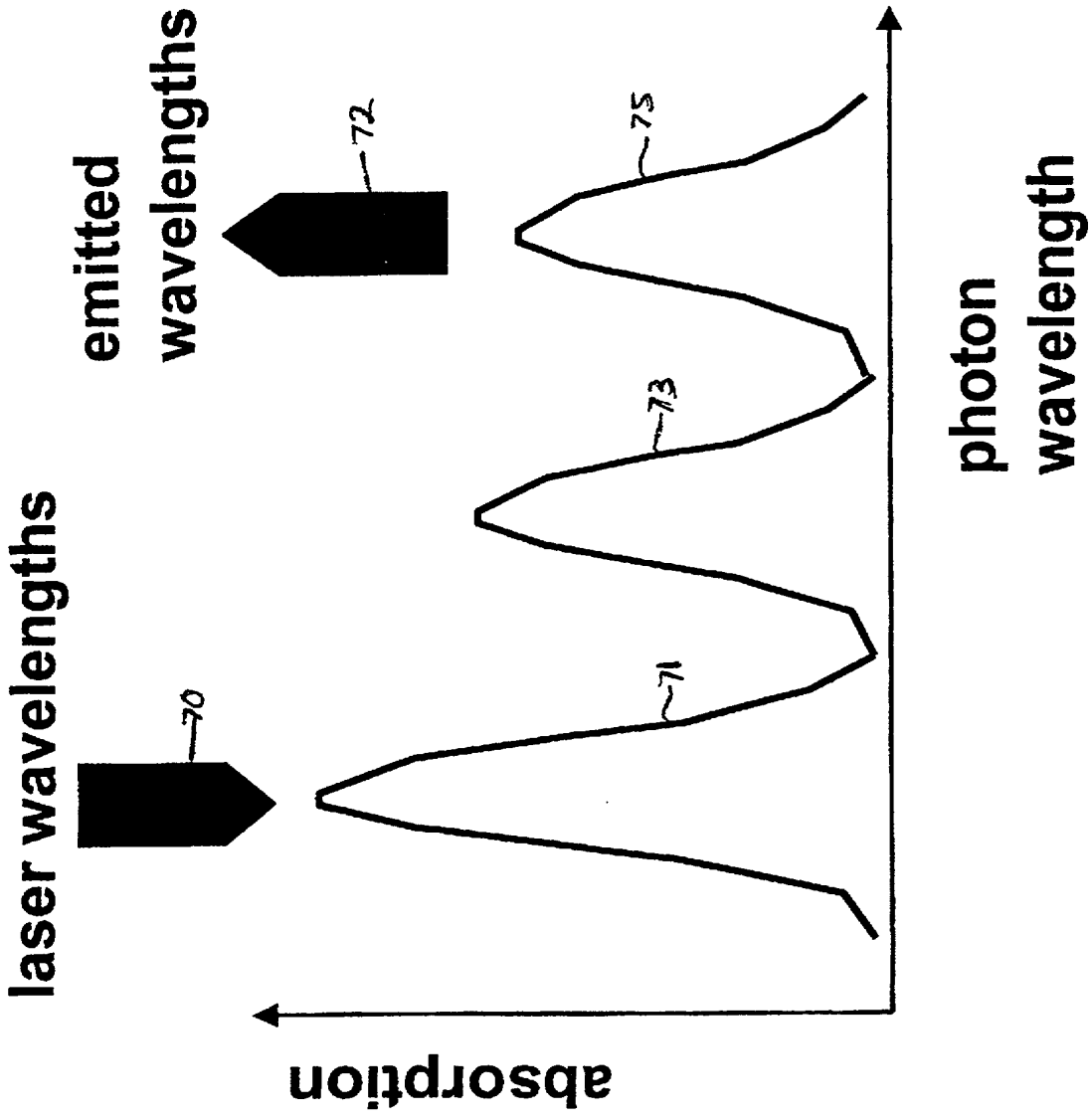
laser wavelengths
emitted wavelengths
absorption
photon wavelength
70
71
72
73
75

Fig.10

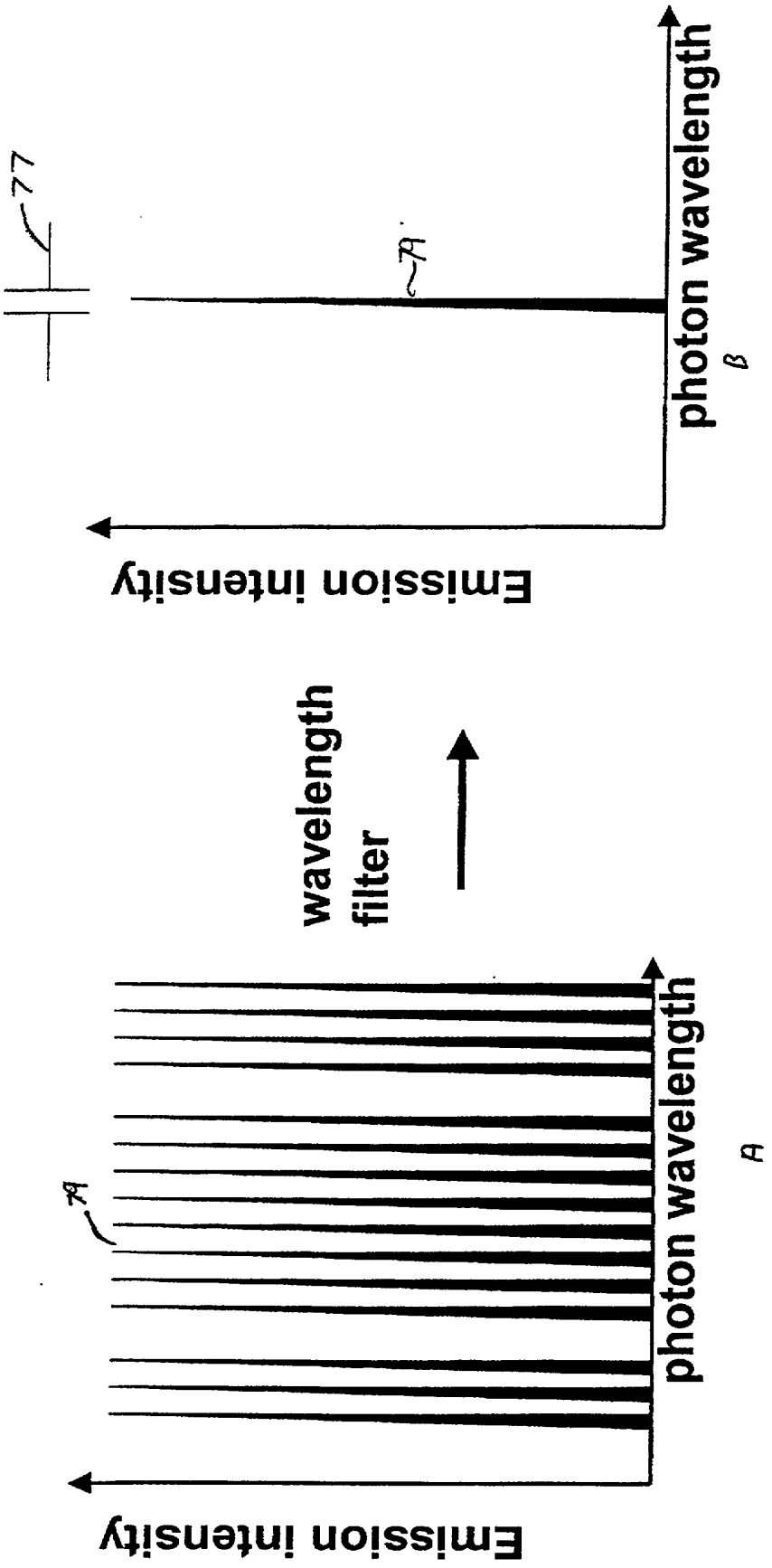
Emission intensity
photon wavelength
A
wavelength
filter
Emission intensity
photon wavelength
B
77
79

Fig.11

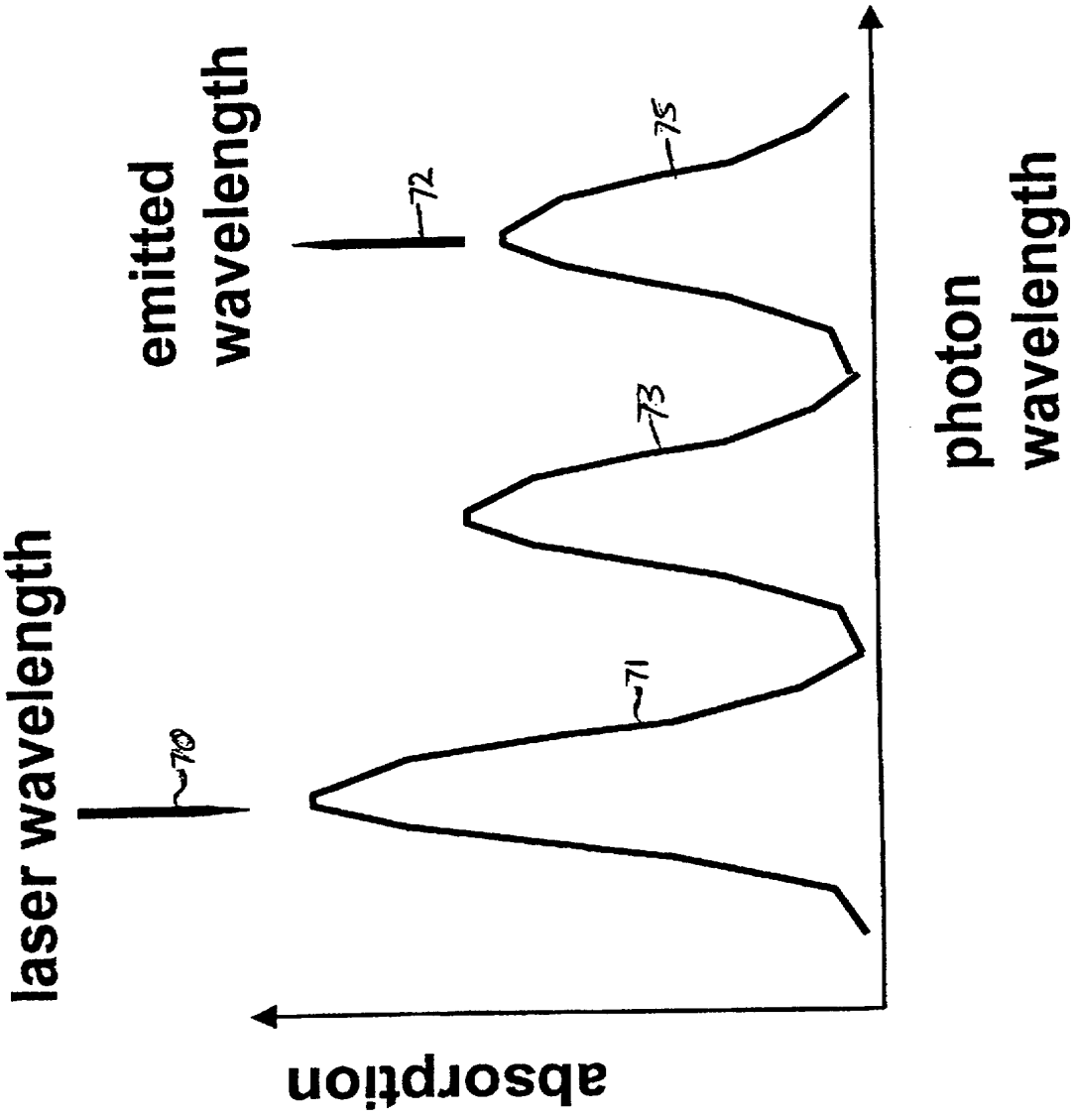
laser wavelength
emitted wavelength
absorption
photon wavelength
70
71
72
73
75

Fig.12

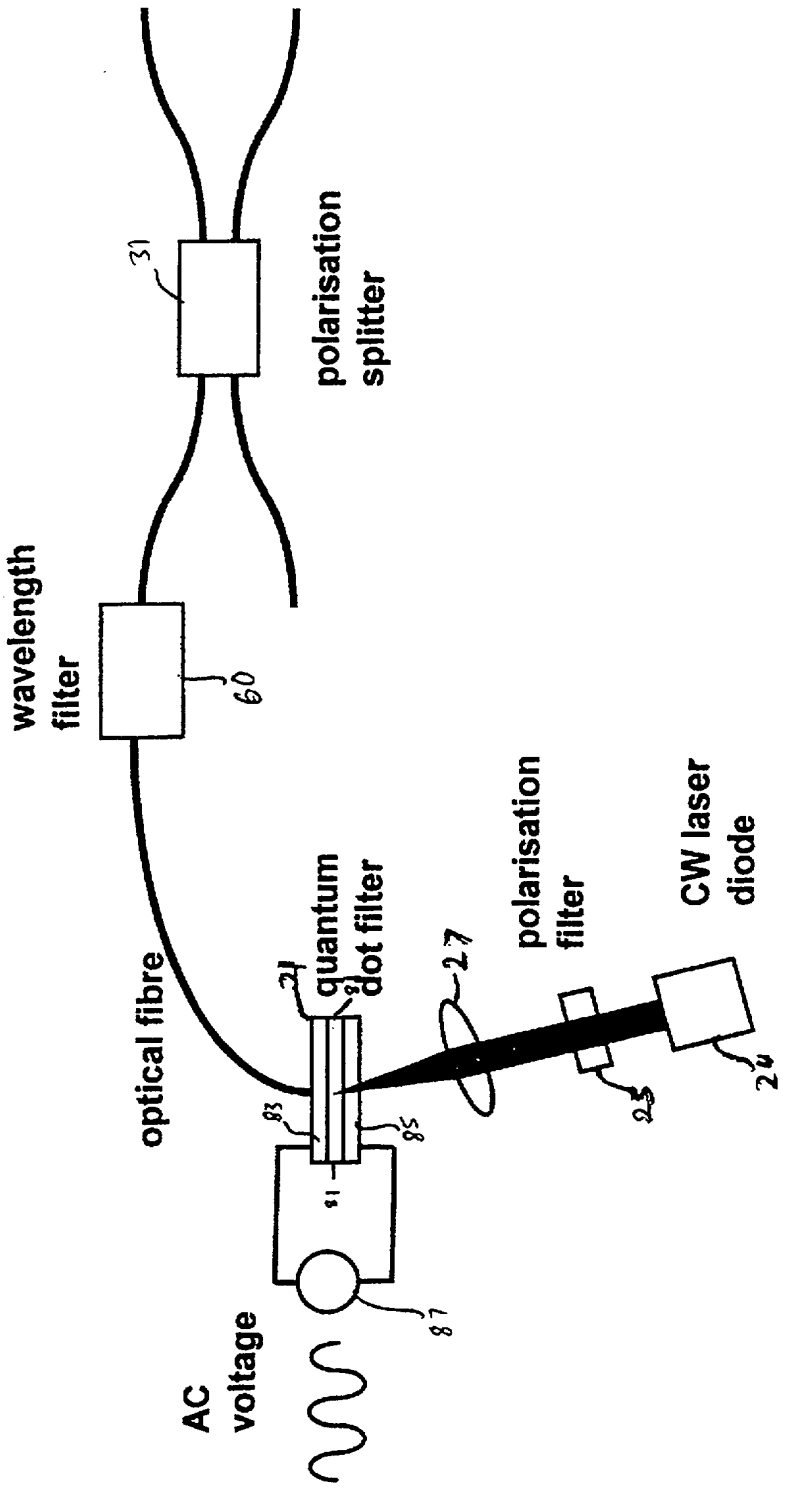
polarisation splitter
31
wavelength filter
60
optical fibre
quantum dot filter
21
27
polarisation filter
CW laser diode
23
25
83
85
11
87
AC voltage

Fig.13

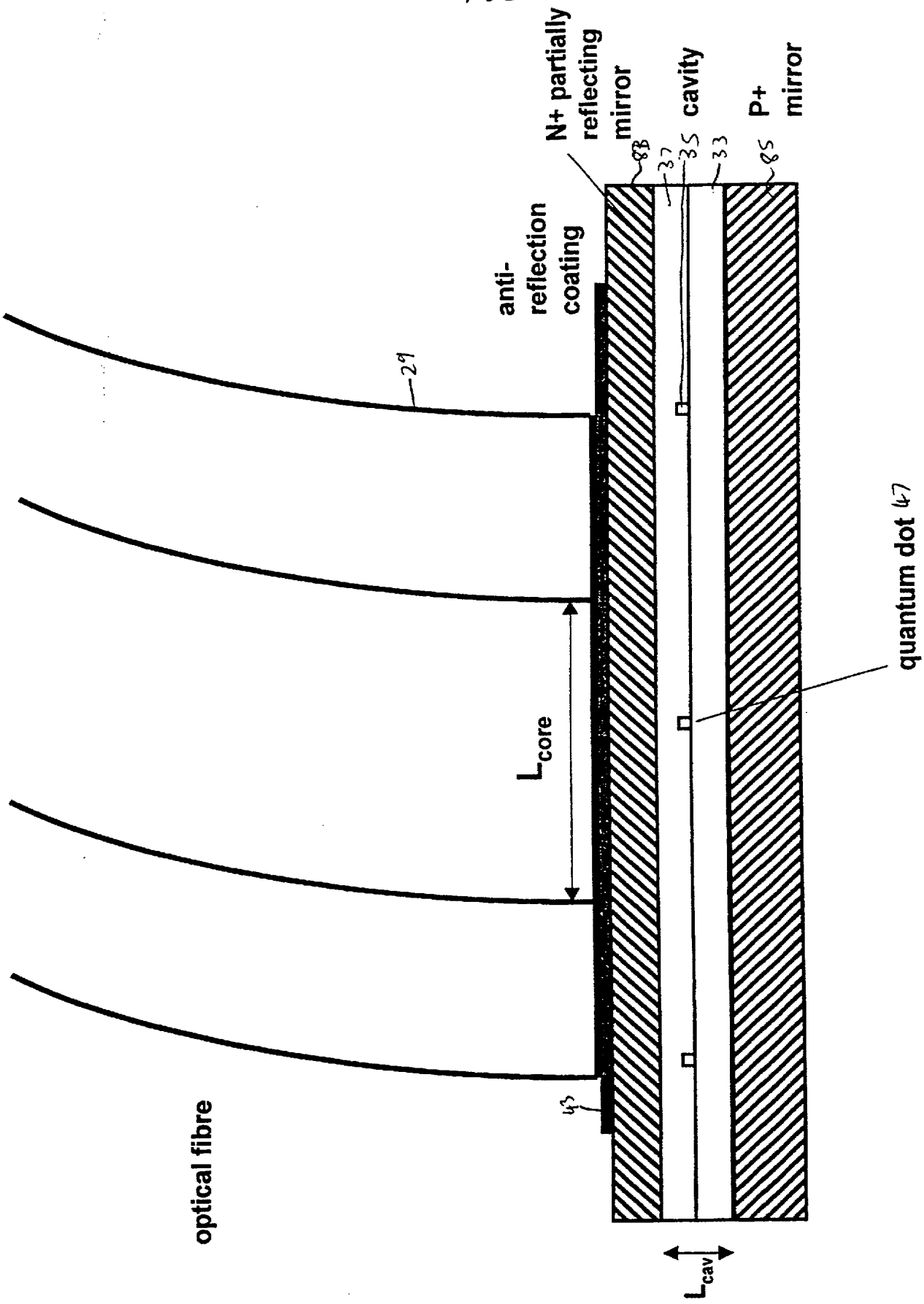
optical fibre
anti-reflection coating
N+ partially reflecting mirror
cavity
P+ mirror
quantum dot 47
L_{core}
L_{cav}
29
43
38
37
35
33
85

Fig.14

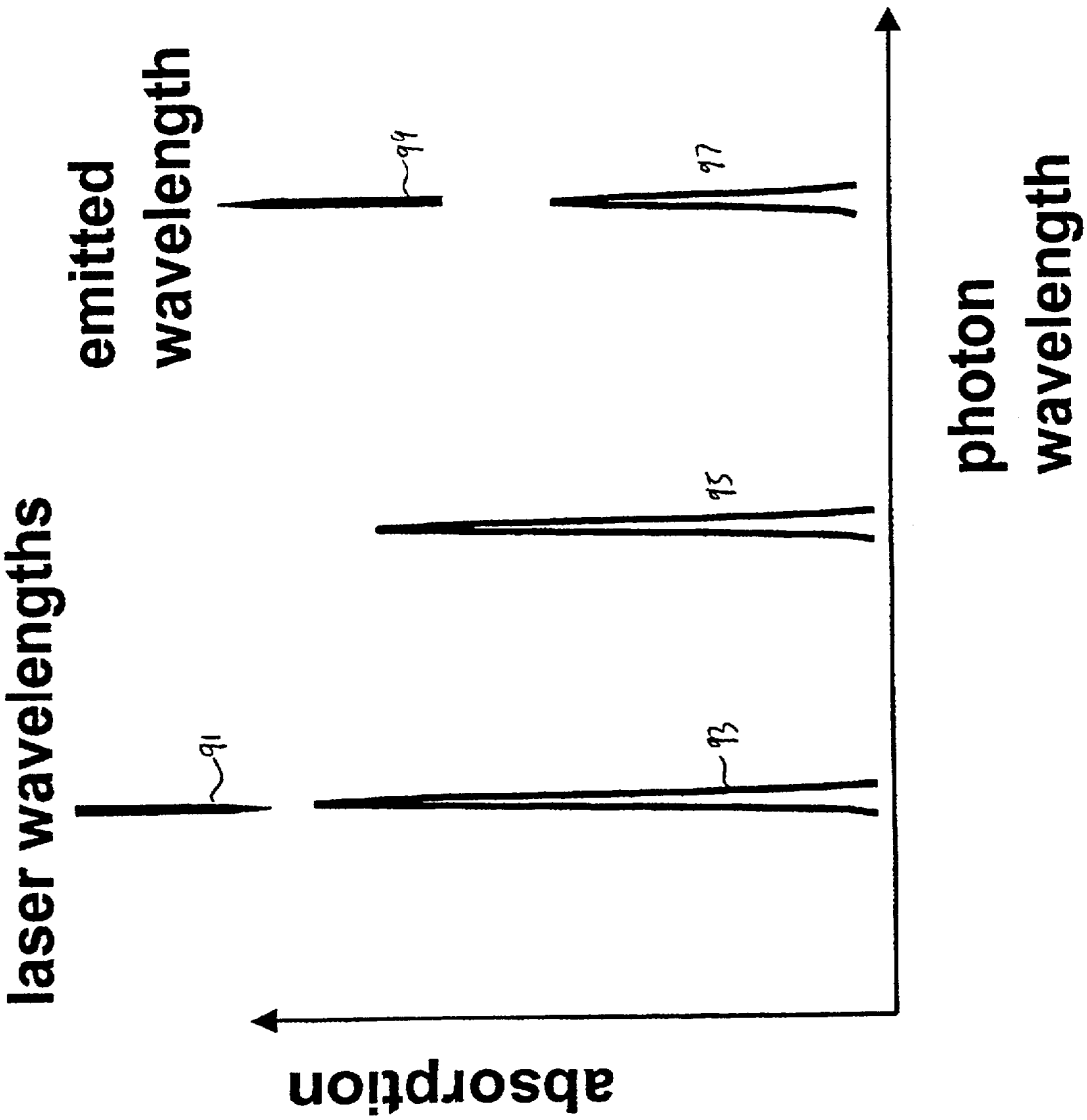
laser wavelengths
emitted wavelength
absorption
photon wavelength
91
93
95
97
99

Fig.15

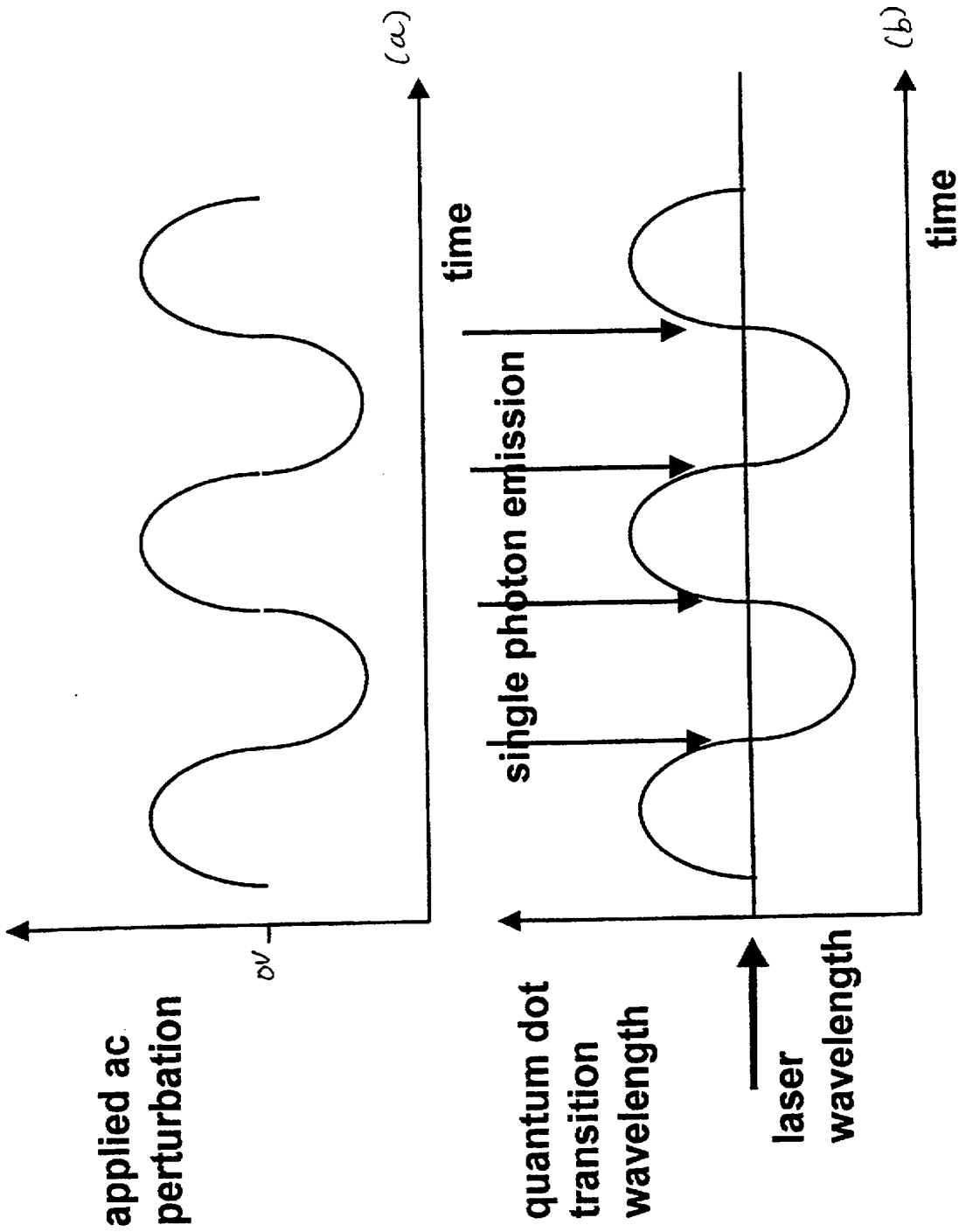
applied ac perturbation
0V
(a)
time
quantum dot transition wavelength
single photon emission
laser wavelength
(b)
time

Fig.16

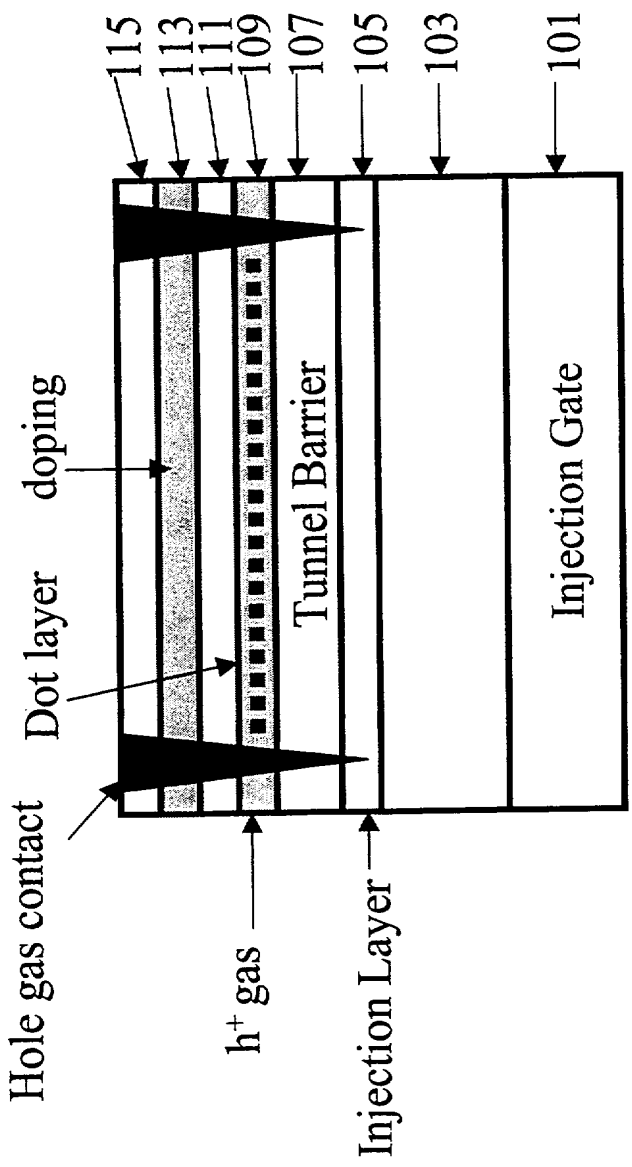
115
113
111
109
107
105
103
101
Hole gas contact
Dot layer
doping
h+ gas
Injection Layer
Tunnel Barrier
Injection Gate
T1
T
V2
V1
Pulse Generator

Fig. 17

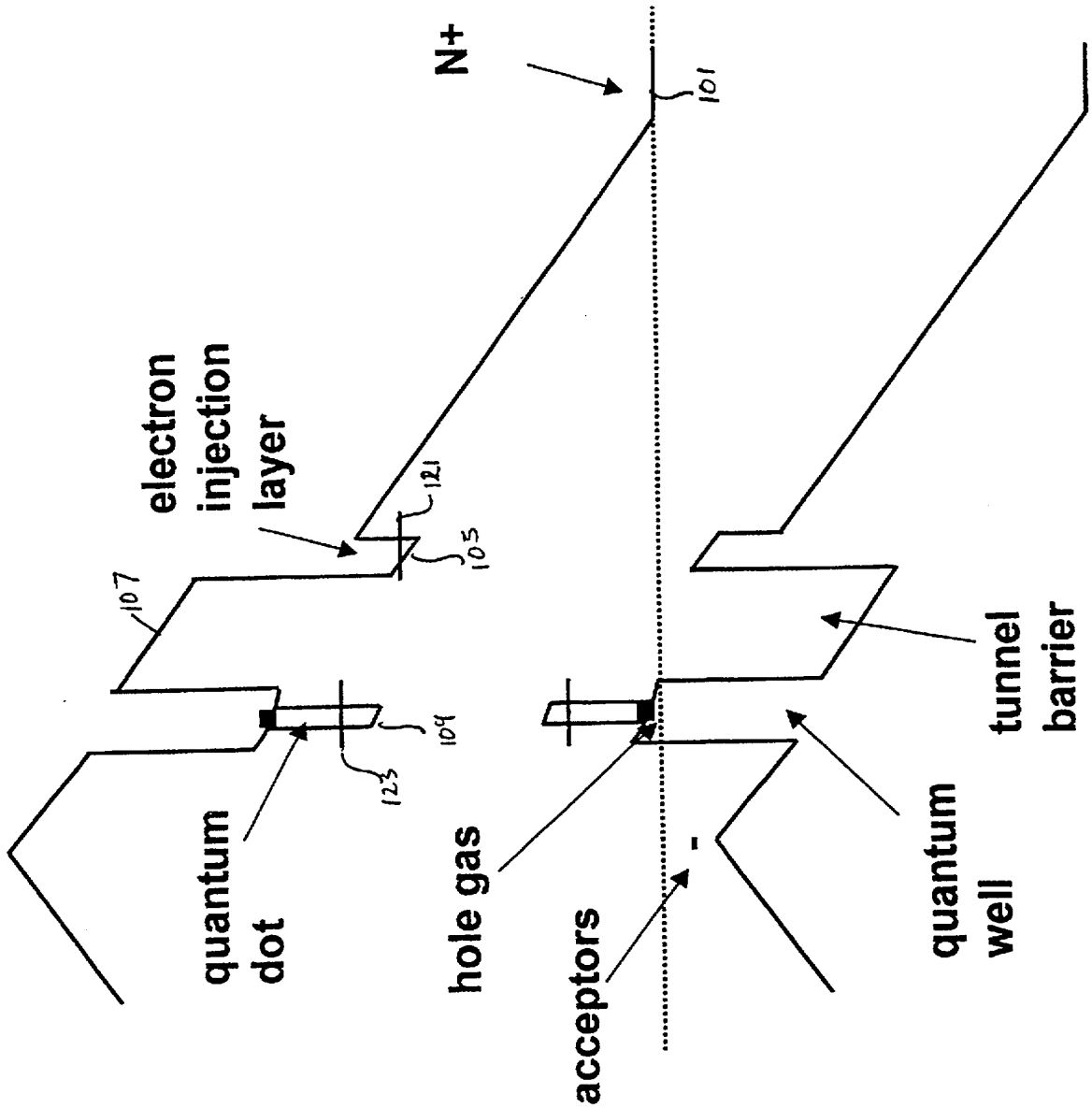
N+
101
electron injection layer
121
105
107
109
123
quantum dot
hole gas
acceptors
quantum well
tunnel barrier

Fig.18

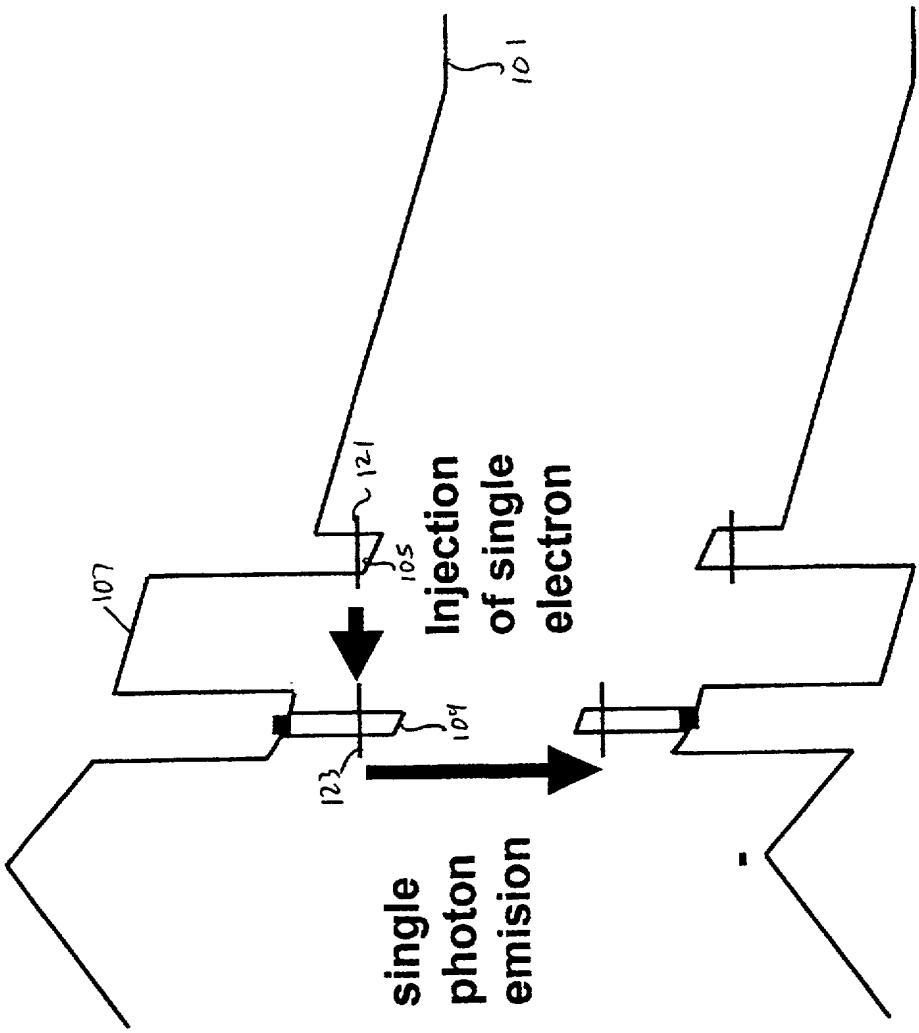
101
121
105
107
Injection
of single
electron
109
123
single
photon
emision

Fig.19

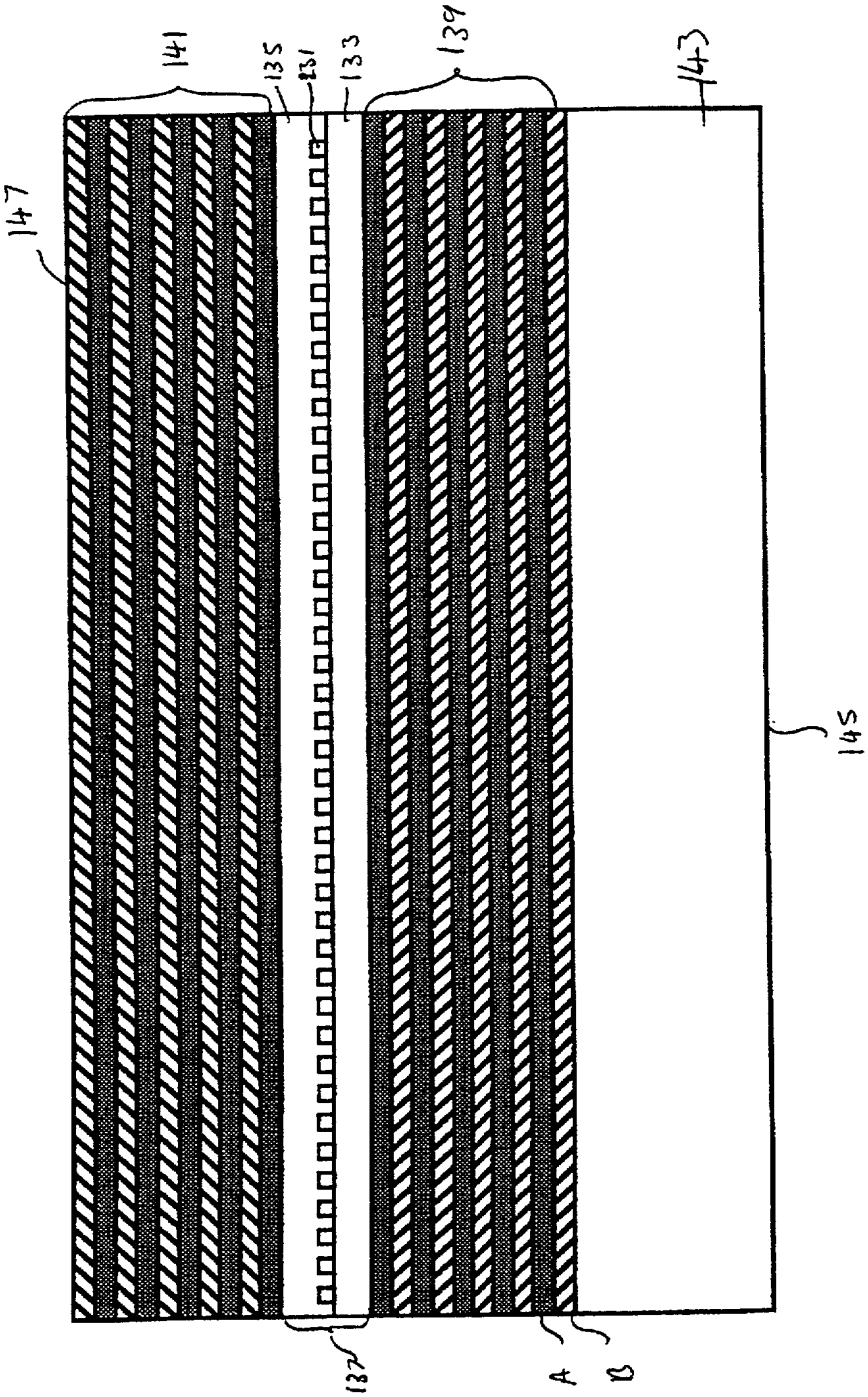

Fig. 20

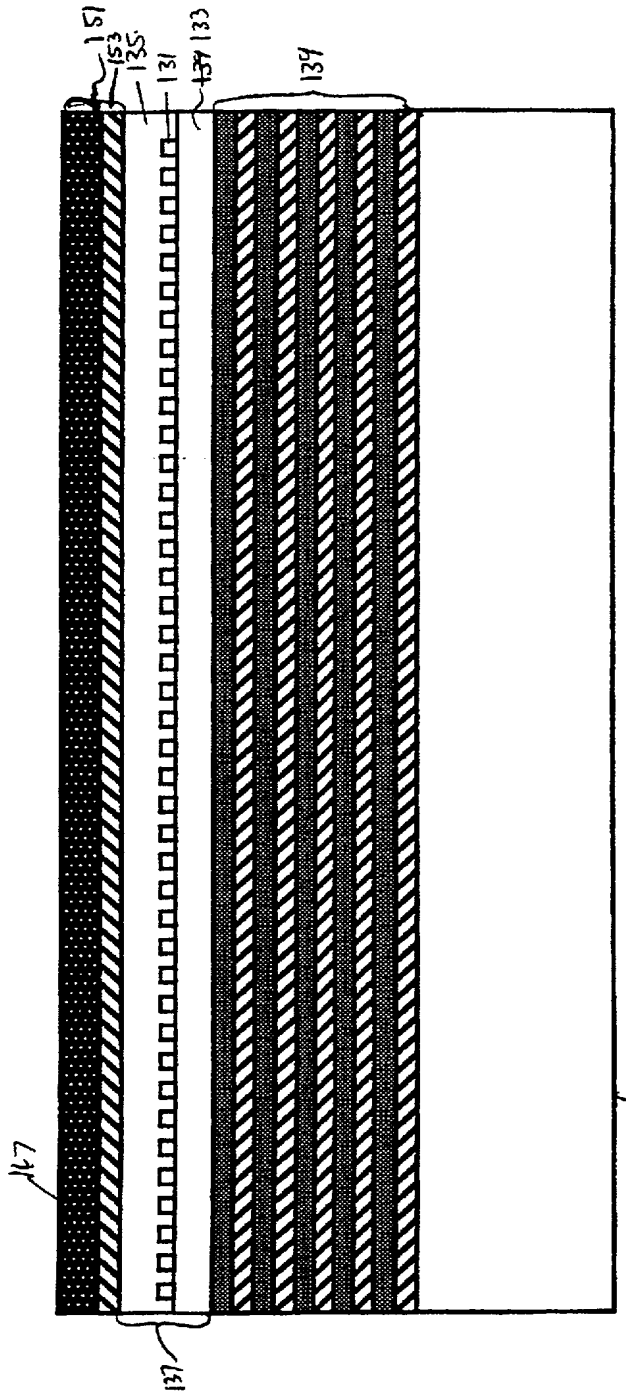

Fig. 21

Prior Art

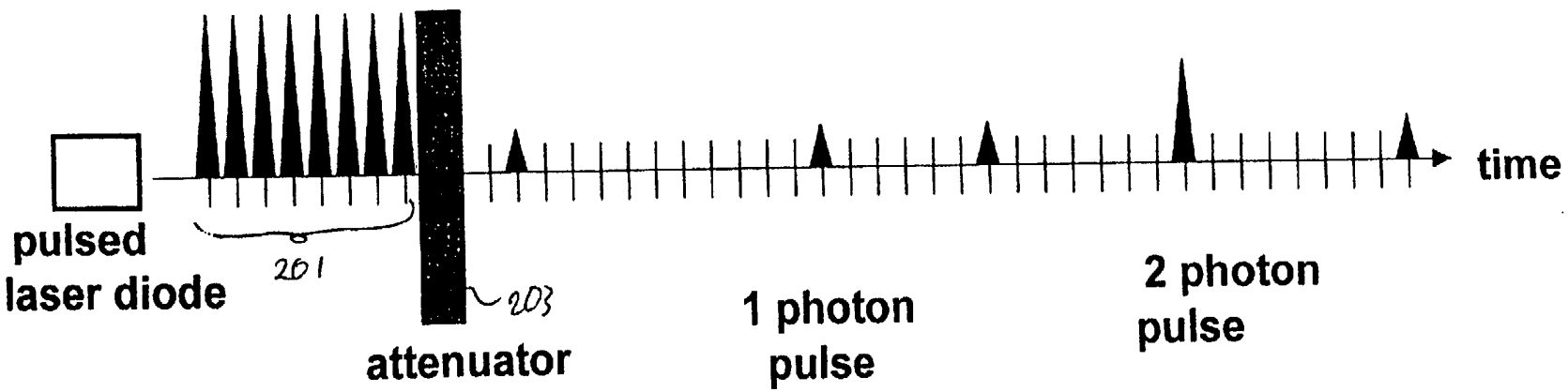

Fig. 22

2377551

A Photon Source

The present invention relates to a photon source. More specifically, the present invention relates to a photon source which is capable of emitting single photons which are spaced apart by a predetermined time interval or pulses of n photons, where n is an integer can be controlled to the accuracy of a single photon.

There is a need for such so-called single photon sources for use in optical quantum cryptography where, for example, the security key for an encryption algorithm is delivered by a stream of single photons which are regularly spaced in time. It is essential for the security of this technique that each bit is encoded on just a single photon. This is because an eavesdropper trying to intercept the key will be forced to measure and thereby alter some photons during reading of the communication. Therefore, the intended recipient of the key can tell if the key has been intercepted.

Such a source is also useful as a low-noise source for optical imaging, spectroscopy, laser ranging and metrology. Normal light sources suffer from random fluctuations in the photon emission rate at low intensities due to shot noise. This noise limits the sensitivity of many optical techniques where single photons are detected. A single photon source which produces photons at regular time intervals has a reduced shot noise.

Previously, single photon sources have been envisaged by strongly attenuating the emission from a pulsed laser source. Such a source is shown in Figure 22. The optical beam 201 is fed through an attenuator 203. The attenuator is configured so that the average number of photons transmitted is about 0.1. Since single photons are

indivisible, this means that about 10% of the periods will contain a single photon, while 90% of them are empty.

This method has two serious drawbacks. First, there is still a small probability of finding two photons within one period. A significant number of these two photon emissions would seriously impinge on the security of the device for quantum cryptography. The second problem is that most of the periods are empty and hence carry no information. Thus, the time which it takes to send the key is increased, and also, the maximum distance over which it can be transmitted is limited. The distance limitation problem arises from the fact that optical quantum cryptography is only effective when the rate of detected photons is much higher than the 'dark count' rate of the detector. Therefore, a system with a high emission rate source can tolerate more transmission loss, and therefore a longer transmission distance medium before being overwhelmed by the detector dark count.

A single photon emitter is also being proposed by J. Kim et al in Nature, **397**, p 500 (1999). The device proposed here utilises an etched single quantum dot. Single electrons and single holes are injected into the etched structure for recombination. The structure suffers from difficulties in injecting a predetermined number of both electrons and holes into the dot for recombination. Also, the proposed fabrication mode is awkward. Also, the method described of forming the quantum dot by etching produces a large number of non-radiative centres, which drastically reduces the emission efficiency of the device and leads to most of the injected electron-hole pairs being lost through non-radiative recombination.

The present invention seeks to address the problems of the above devices. In a first aspect, the present invention provides a photon source comprising a quantum dot having a first confined energy level capable of being populated with an electron and a second confined energy level capable of being populated by a hole; and

supply means for supplying carriers to the said energy levels, wherein the supply means are configured to supply a predetermined number of carriers to at least one of the

energy levels to allow recombination of a predetermined number of carriers in said quantum dot to emit at least one photon.

The present invention is capable of emitting a single or n photons at a predetermined time (where n is an integer). The present invention may be used to produce a stream of single or n photons at predetermined time intervals. For instance, it would produce a cyclic generation of single or n-photons spaced by constant time intervals.

The present invention is capable of being configured to product a single photon or a group of n photons at a predetermined time. It may also be configured to repetitively produce single photons or groups of n photons at a predetermined time or times. The time between successive photon emissions can be controlled, successive photon emissions (be it single photons or n photons) will preferably be regularly spaced in time. Although, the source may be configured to irregularly space successive photon emissions.

The first confined energy level is commonly termed a conduction band energy level and the second confined energy level is known as a valence band energy level. The present invention operates by controlling the number of carriers which is supplied to either the conduction band level or the valence band level or both.

It is apparent to persons skilled in the art that, in a quantum dot, there may be a first confined energy level which is a ground state, and subsequent further excited conduction band levels. Similarly, the quantum dot may have more than one confined valence band level. Thus, there are several possible optical transitions of a quantum dot which can absorb a photon.

Preferably, the supply means of the present invention are configured to supply a stream of single (or an integer number n) carriers at predetermined time intervals to the at least one energy level. Further, the stream of single (or n) carriers are configured so that a stream of single (or n) photons are emitted at predetermined time intervals. The source

may be configured as a single electron source wherein single carriers are repetitively supplied to the said at least one energy level such that a single photon stream is produced. In such a single photon stream, each of the single photons are separated from one another by predetermined time intervals.

The supply means fulfils two functions, it supplies carriers to the confined energy levels, in addition, it also controls or triggers the supply of carriers to the energy levels.

The supply of carriers to the relevant energy levels, in addition to the control of the supply of carriers can be achieved in a number of different ways.

The photon source may be radiated with radiation which is configured to excite a predetermined number of electrons and holes within the first and second energy levels respectively.

As previously mentioned, there may be many conduction band levels into which electrons can be excited, similarly, there may be many valence band levels. If an electron is supplied to an excited energy level of the conduction band then the electron will almost certainly relax into a lower energy state or the ground state of the conduction band prior to recombining with a hole. The time which a carrier spends in a energy state before relaxing to a lower energy state is known as the 'relaxation time'. As used hereinafter, the relaxation time will be taken to mean the average time which a carrier remains in an energy state before releasing to another energy level. As used hereinafter, the recombination time will be taken to mean the average time it takes for an electron and hole to recombine. Usually carriers will undergo relaxation more quickly than recombination. This is especially true when the carriers are created in the excited levels of the quantum dot, as in this case, the carriers usually relax to the ground states of the quantum dot before recombination. However, in some situations, relaxation may occur by recombination.

An electron from the ground state may recombine with a hole to emit a photon. Alternatively, an electron from an excited state may recombine with a hole to emit a photon. It should be noted that although it is possible that an electron from a higher energy state to combine with a hole, the probability of this transition occurring is very small, as it is far more likely that the electron will first relax into the ground state prior to recombination.

To excite the carriers into the conduction and valence bands for recombination, the source is illuminated with radiation which is configured to excite either a ground state transition within the quantum dot or, an excited transition. This is achieved by tuning the wavelength of the radiation to the appropriate optical transition energy of the quantum dot. The required transition energy may be that to excite an electron into the ground state of the conduction band and a hole into the ground state of the valence band of the quantum dot. Alternatively, it may be required to supply the electron and/or hole into one of the excited energy levels of the quantum dot. In the quantum dot, the confined conduction band (valence band) levels can only accommodate a maximum of two carriers. One of these carriers is of a spin up and the other electron is of a spin down configuration.

It is possible to configure the structure so that only one electron is excited into a level of the quantum dot by the radiation. This can be done by either polarising the incident light so that it circularly polarised with a single orientation direction (i.e. either left or right). Or, a magnetic field can be applied to the device to lift the spin degeneracy of the conduction band level. Only one electron can then be accommodated in a single conduction band level.

Also, the absorption of the first electron hole pair by the dot results in a shift in the transition energy of the dot. The spectral line width of the laser can be tuned to be smaller than this shift in energy. Thus, only a single electron hole pair can be excited at a time.

For the purpose of explaining the operation of the device, it will be assumed that there is only one electron in the conduction band of the quantum dot. A hole will also be excited into the valence band layer when the electron is supplied to the conduction band layer.

The electron and the hole will recombine to emit a photon during a characteristic time called the recombination time. If the incident radiation has an energy equal to that of the lowest energy transition energy of the quantum dot and the radiation is pulsed with a duration shorter than the relaxation time, then by the time the electron and hole have relaxed, no radiation is present to excite a second electron and hole. Therefore, only a single photon is emitted.

Also, the time between the leading edges of the incident pulses should be longer than the recombination time. This is to prevent a second pulse arriving at the quantum dot before the electron and hole have recombined.

If the radiation photon energy is tuned to the energy of an excited (i.e. not lowest energy) transition of the quantum dot, the photoexcited electron and hole will relax to their ground energy levels in the dot before recombination. If the duration of the pulse is shorter than the relaxation time, then only a single electron and hole can be excited per pulse of the exciting radiation. Therefore, only a single photon is emitted.

If the conduction band contains two electrons, the two photons which are emitted can be separated by filtering out the unwanted photons with a polarisor. If two electrons recombined with two holes, then the two photons emitted will have different polarisations. Therefore, a polarisation splitter will allow a regular stream of single photons with predetermined polarisation to be produced.

Also, if the degeneracy of the levels is lifted by a magnetic field, the emitted photons will have different energies depending on the specific transition. Hence, it is possible to filter out photons emitted at the other energies to obtain a stream of single photons.

In order to excite a particular transition in the dot, i.e. in order to populate a certain conduction band level (i.e. the ground state or an excited level), the dot is irradiated with radiation having an energy substantially equal to that of the required energy level.

Often it is convenient to prepare a device with more than one quantum dot. Often these quantum dots possess different transition energies due to fluctuations in their size or composition. In this case, the emission from a single quantum dot may be isolated by filtering the wavelengths of the emitted light. By allowing only the light in a narrow bandpass to pass it is possible to collect the emission of a single dot and exclude that of the others.

Preferably, the area of the source from which light is collected contains at most one thousand optically active quantum dots.

Alternatively, it is possible to selectively excite a single quantum dot by using a laser with a narrow wavelength spectrum. The laser will excite only the quantum dot which has a transition energy equal to the laser energy.

It is also possible to produce an n-photon source if a dot is produced which has transition energies which lie close enough to one another such that it is possible to excite more than one transition at a time. Another possible way to produce an n-photon source is to use several excitation wavelengths in the incident pulse.

In these devices with more than one quantum dot, it is possible to change the quantum dot from which light is collected by changing the wavelength bandpass energy or the laser energy.

The selected population of an electron or hole level can also be achieved using continuous radiation (i.e. non-pulsed). If the photon source is irradiated with radiation corresponding to a particular transition energy within the quantum dot, the population of

the quantum dot level can be controlled by periodically varying the transition energy of the quantum dot. This can be done in many ways, for example, the electric field across the dot may be varied by an applied AC voltage. Also, the carrier density of the dot or surrounding layers, the magnetic field applied to the quantum dot and even the temperature of the quantum dot can all be modulated to vary the transition energy of the quantum dot.

The transition energy of the quantum dot can be modulated so that the confined energy level is only capable of being populated by carriers for a certain time. This should be less than the relaxation time of the photoexcited electron-hole pair. Therefore, although the radiation intensity is constant, light can only be absorbed by the quantum dot for the short time that the transition energy equals radiation energy. The electron and hole can then recombine to emit a photon in the same way as described with reference to excitation by the pulsed laser. Sometime later, the transition energy of the quantum dot will be swept through the laser energy again and the dot is able to absorb an electron and hole again. Again, the degeneracy of the level may be lifted by application of a magnetic field or, a single electron may be introduced into the level by polarisation of the incident radiation. As before, the emitted radiation can be filtered to remove emitted light from the specific polarisation or to remove photons which arise due to recombination within other quantum dots.

Previously, the discussion has concentrated on illuminating the device in order to supply carriers for the conduction valence band. However, the present invention may also operate by populating either of the conduction or valence bands by injection of carriers into the conduction or valence band level. In such a structure, in order to obtain fine control, it is preferable if either the conduction band levels or the valence levels are continually populated with excess carriers. The remainder of the discussion will concern a device where the valence band levels are populated with excess holes and electrons are injected into the conduction band. However, it will be appreciated that the inverse device can be fabricated where the conduction band levels are populated with excess electrons, and holes are injected into the valence band.

The holes are preferably provided to the valence band of the quantum dot via a doped barrier. Such a doped barrier will preferably be a remotely doped or modulation doped barrier which is separated from the quantum dot by a spacer layer.

Preferably the quantum dots are placed within a two dimensional excess carrier gas so as to provide the excess carriers.

Preferably at least one ohmic contact is made to the two dimensional carrier gas so as to repopulate the carrier gas after recombination of an excess carrier with an injected carrier.

Electrons are injected into a conduction band level of the dot. As with the previously described optically by excited sources, the injected electron and a hole recombine and emit a photon. To avoid more than one photon emission, the electrons are preferably injected one at a time. A particularly preferable way of injecting the electrons is to use resonant tunnelling through a barrier layer. Here, the energy of the injected electrons is matched to the energy of a conduction band level in the quantum dot. To achieve selected injection of electrons, the energy of the electrons to be injected is periodically varied so that the device is switched between an ON state (where the energy of the injected electrons aligns with that of the conduction band level within the quantum dot) and an OFF state (where the injected electrons do not align with the conduction bands within the quantum dot). In the OFF state, electrons cannot tunnel into the quantum dot.

The present invention may comprise a plurality of quantum dots. In such a device, it is virtually impossible to make a plurality of quantum dots which will have identical transition energies. Therefore, it is possible to select emission from a single quantum dot by filtering the wavelengths of the collected light. There is also a variation in the transition energy from dot to dot which may be due to fluctuations in the size or composition of the dots for instance. Thus, it is possible to selectively inject carriers into just one of the quantum dots.

In the above described device, this can be achieved by precise control of the voltage in the "ON" state. Alternatively, it may be possible to control the energy of the illuminating radiation to excite a transition in a single dot.

Preferably, the area of the source from which light is collected should contain, at most 1000 optically active quantum dots.

Once the photon is emitted from the quantum dot, it can be collected by an optical fibre. Preferably, the device is provided with a coupling means to allow the photons to be efficiently collected by a fibre optic cable. Such coupling means may comprise antireflection coating located on the surface of the device through which the emitted photons are collected. Also, the antireflection coating could be located on the optical fibre itself.

The coupling means may also comprise a lens to collect emitted photons.

A particularly preferable arrangement of the device is achieved if the source has a mirror cavity which has two mirrors located on opposing sides of the quantum dot. Preferably, one of the mirrors (ideally the mirror closest the output surface) is partially reflective such that it can transmit the emitted photons. More preferably, the energy of the cavity mode for said mirror cavity is preferably substantially equal to that of the emitted photons. Further, it is preferable if the distance between the two mirrors L_{cav} of the cavity is defined by

$$L_{cav} = \frac{m\lambda}{2n_{cav}}$$

where m is an integer, n_{cav} is the average refractive index of the cavity and λ the emission wavelength (in vacuum).

The advantage of using a cavity is that it allows more of the emitted light to be coupled into the numerical aperture of the collecting fibre or optic. The cavity mode of the resonant cavity is emitted into a narrow range of angles around the normal to the mirrors. The fibre/collection optic is arranged to collect the cavity mode.

At least one of the mirrors may be Bragg mirror comprising a plurality of alternating layers where each layer satisfies the relation:

$n_a t_a = n_b t_b = \lambda/4$

Where one dielectric layer (A) has a refractive index of n_a and a thickness of t_a and second dielectric layer (B) has a refractive index of n_b and a thickness of t_b.

At least one of the mirrors may also comprise a metal layer. A phase matching layer should also be located between the cavity and the metal layer, so that an antinode is produced in the cavity mode at the interface between the cavity and phase matching layer. At least one of the mirrors may even be a semiconductor/air or semiconductor dielectric interface.

In the device with multiple quantum dots, the cavity is preferably designed so that only one of the quantum dots has an emission energy which couples to the cavity mode. This can be used to ensure that emission from only one dot is collected producing just single photons.

In this case, the energy width or band-pass of the cavity mode should be approximately equal to the linewidth of the emitting quantum dot. This can be achieved by configuring the design of the cavity as required - in particular the reflectivities of the cavity mirrors.

The width of the cavity mode decreases with increasing mirror reflectivity. The mirror reflectivities can be increased by increasing the number of periods in a Bragg mirror.

The device has been described with one optical fibre. However, it will be appreciated that the device can be fabricated with more than one quantum dot emitting into more than one fibre.

A particularly preferable method for fabricating the quantum dot(s) of the present invention is by use of a self-assembling growth technique (such as the Stranskii Krastinow growth mode). Therefore, in a second aspect, the present invention provides a method for the fabrication of a single photon source, the method comprising the step of forming a quantum dot layer by growing a layer of a first material on a second material, wherein there is a variation in the lattice constants between the first material and the second, the first material being deposited in a layer which is thin enough to form a plurality of quantum dots, the method further comprising the step of providing supply means for supplying carriers to the said energy levels, wherein the supply means are configured to supply a predetermined number of carriers to at least one of the energy levels in the quantum dots to allow recombination of a predetermined number of carriers in said quantum dot to emit at least one photon.

Typically, the first material will be InAs, InGaAs or InAlAs and can be grown to a thickness of preferably less than 50 nm. The second material will preferably be GaAs or AlGaAs.

Preferably the method of the second aspect, will further comprise the step of forming a layer of a third material overlying the first material. The third material may be the same as the second material.

The areal density of the quantum dots is preferably less than $3x10^7cm^{-2}$.

The present invention will now be described with reference to the following preferred, non-limiting embodiments in which

Figure 1 shows a schematic band structure of a single quantum dot;

Figure 2 shows a quantum dot filter for a single dot in accordance with an embodiment of the present invention;

Figure 3 shows a single photon emitter according to an embodiment of the present invention coupled to an optical fibre;

Figure 4 shows a single photon emitter in accordance with an embodiment of the present invention located within a resonant cavity;

Figure 5 shows a single photon emitter according an embodiment of the present invention coupled to a collection lens;

Figure 6 shows an absorption spectra for a single photon emitter in accordance with an embodiment of the present invention;

Figure 7 shows a multiple quantum dot single photon emitter in accordance with an embodiment of the present invention;

Figure 8 shows the single photon emitter of Figure 7 coupled to an optical fibre;

Figure 9 shows the single photon emitter of Figure 7 provided within a resonant cavity;

Figure 10 shows a schematic absorption spectra of the embodiment of Figure 7;

Figure 11 shows schematic plots to illustrate filtering of the wavelength of the embodiment of Figure 7;

Figure 12 shows an absorption spectra for the embodiment of Figure 7 with filtration;

Figure 13 shows an electrically triggered single photon source in accordance with an embodiment of the present invention;

Figure 14 shows the embodiment of Figure 13 coupled to an optical fibre;

Figure 15 shows an absorption spectra for the embodiment of Figure 13;

Figure 16 shows a plot showing the variation in AC perturbation with the quantum dot transition wavelength of the embodiment of Figure 13;

Figure 17 shows and electrically injected quantum dot single photon emitter;

Figure 18 shows a band structure of the device of Figure 17 when in an OFF condition;

Figure 19 shows a band structure of the device of Figure 17 when in an ON condition;

Figure 20 shows in detail a structure of a single photon source according to an embodiment of the invention located within a resonant cavity;

Figure 21 shows a variation in the resonant cavity of Figure 20;

Figure 22 shows a prior art emitter.

Figure 1 shows a schematic band structure of a single quantum dot 1. The quantum dot forms a minimum in the conduction band 3 and a maximum in the valence band 5. A plurality of quantised conduction band levels 7 are formed in the minima 9 and a plurality of valence band levels 11 are formed in valence band maximum 13.

When a conduction band level 8 is populated by electron 15 and a valence band level 12 is populated by hole 17, the electron and hole recombine. Recombination of the single electron and a single hole results in the emission of a single photon.

The recombination of an electron and hole does not incur the instant that an electron and a hole populate the combined energy levels 7, 11. Instead, there is, on average, a finite delay between the population of the two levels and the emission of a photon. This is known as the "recombination time". In a beam of conventional laser light, there are many photons. It is impossible using attenuation of a laser beam alone to obtain a regular stream of photons. However, in the quantum dot shown in Figure 1, a photon is emitted only when an electron and hole recombine. Therefore, providing that electrons and holes can be supplied to the dot one by one at regular time intervals and that the recombination time is shorter than the time between population of both confined energy level 7, 11, a stream of single photons can be produced.

The above described situation where an electron is excited into the conduction band and then recombines with a hole is an oversimplification of the process. The electron can occupy any one 8 of a plurality of levels 7 in the conduction band 9. If the electron and hole in the quantum dot are excited optically, then the actual level 8 occupied by the electron and hole initially, is dependent on the wavelength (or energy) of the incident light. The actual level 8 occupied by the electrons is, initially dependent on the wavelength (or energy) of the incident light. The electron may be excited into the ground state conduction band level from which it will decay to recombine with a hole, or it may be excited into an excited conduction band level. From such an excited level, the electron will most probably relax into a lower energy level in the conduction band before recombination. The time which a carrier takes to transfer from an excited level to a lower level is known as the "relaxation time". Generally, it is more statistically favourable if the carrier decays from an excited state to the ground state conduction band before recombination.

Figure 2 shows an embodiment of the present invention. Here, the electron 15 and hole 17 are excited into the confined energy levels 7, 11 respectively by excitation of the photon source 21 by a pulsed laser diode 23. A first pulse arrives at the quantum dot and excites an electron hole pair. Once an electron hole pair is excited, no further radiation can be absorbed by the dot. The pulse duration should be shorter than the relaxation time of the carriers. If the pulse duration was longer than the relaxation time then a carrier which had been excited into an excited conduction band level might relax during illumination of the dot. This would mean that a second electron/hole pair could be excited in a single pulse of radiation. The time between the leading edge of subsequent pulses should be longer than the recombination time so as to allow excitation of an electron-hole pair by the next pulse. Therefore, the electron and hole pair should recombine before the next pulse arrives. By using this technique, it is possible to produce a stream of single photons.

In Figure 2, the laser pulse is passed through a polarisation filter to select the required polarisation, be it one of the orthogonal components of left or right circularly polarised. The polarised beam is then focused onto the single photon source 21 by lens 27. The output from single photon source 21 is then coupled into optical fibre 29. Optical fibre 29 is then fed through polarisation splitter 31 which is capable of separating the two orthogonally polarised components of the emitted photon beam.

Figure 3 shows the coupling between device 21 and optical fibre 29 in more detail. Device 21 comprises an under layer 33 formed on an upper surface of substrate 31. A dot layer 35 is then formed on an upper layer of under layer 33 and an over layer 37 is then formed overlying dot layer 35. The top surface 39 of over layer 37 is an output surface. Single photons emitted from the quantum dot layer 35 are transmitted through this surface 39. The beam from the pulsed laser diode 23 is incident on the lower surface 41 in this example. However, it should be noted that the beam could also be incident on the upper surface or side of the device.

An anti-reflection coating 43 is formed overlying the output surface 39. Optic fibre 29 is located on said anti-reflection coating. The optical fibre is situated so that the core 45 of the fibre is located so that it overlays one quantum dot. Thus, only the emission from this single quantum dot 47 is collected by the fibre. The core of the single mode optical fibre 29 is designed for a wavelength of 1.3μm having a diameter of a few microns.

Therefore, to ensure collection of the emission from a single quantum dot, the area density of the dots should be less than ~$2 \times 10^7 cm^{-2}$. Optical fibre 29 also has a relatively high numerical aperture so as to collect as much of the emitted light as possible. The anti-reflection coating 43 serves to increase the coupling efficiency between optical fibre 29 and photon source 21.

Figure 4 shows a variation on the single photon source of Figure 3. Here, the source 21 has an optical cavity. A dot layer 35 is formed overlying the upper surface of under layer 33. Over layer 37 is then formed overlying the quantum dot layer 35. The under layer, quantum dot layer and over layer are located within a resonant cavity. The resonant cavity comprises a lower mirror located at the lower surface of said under layer 21 and an upper mirror 53 located on an upper surface of said over layer 37. The anti-reflection coating 43 is then provided on the output surface 39 which is now the upper surface of the upper mirror 53.

The upper mirror is partially reflecting so that it can let light escape the resonant cavity formed between the upper mirror 53 and the lower mirror 51. This arrangement functions to modify the angle of distribution of light emitted by the photon source 21 and thus, couple more of the emission into the optical fibre 29.

The optical cavity also strongly influences the spontaneous emission process. Upper 53 and lower 51 mirrors inhibit the escape of light from the top and bottom of the cavity. However, light with a wavelength λ which satisfies the condition

$$L_{cav} = \frac{m\lambda}{2n_{cav}}$$

where m is an integer, n_{cav} is the refractive index of the cavity and L_{cav}, the width of the cavity, is able to escape the cavity. These wavelengths are often referred to as the 'cavity mode'. The cavity strongly modifies the angular dispersion of the emitted light with the cavity mode emitted into a cone centred normal to the plane of the mirrors 51, 53. To achieve maximum coupling efficiency into the optical fibre, the thickness of the cavity is designed to be resonant with a wavelength of the emitting dot. For maximum coupling, the quantum dot is placed at an anti-node of the standing wave pattern between the two mirrors 51, 53.

In Figure 5, the emitted photons are collected by lens 55. The structure of the photon source 21 is identical to that described with reference to Figure 3. Therefore, to avoid unnecessary repetition like reference numerals have been used to describe like features. To ensure that only the light from a single quantum dot 47 is collected by lens 55, the upper surface of the anti-reflective coating 43 has been covered by an opaque film 57. An aperture with a diameter 'L' of between 0.05 and 5 microns has been formed in the opaque film above quantum dot 47 to allow transmission of photons from this quantum dot 47 to the lens 55.

A schematic absorption spectrum of a quantum dot 47 is shown in Figure 6. Absorption is plotted along the Y axis (arbitrary units) and photon wavelength is plotted along the X axis (arbitrary units). The input laser beam is tuned to a transition energy of the quantum dot. The transition energy may be the lowest energy, ground state transition of the quantum dot or, it might be a transition involving excited electron or hole states. The transition energy may be to excite an electron into the conduction band or, it might be to excite an electron from one energy state in the conduction band to an excited energy state in the conduction band. Figure 6 shows the case where the input beam is tuned to an excited transition, (i.e. not the lowest energy transition) of the quantum dot, creating electrons and holes in the excited levels of the dots. In this case, stray excitation light can be removed by spectral filtering.

The excited electrons and/or holes relax into the ground state levels of the quantum dot and recombine, thereby emitting light at the band-gap wavelength of the quantum dot.

The low degeneracy of the quantum dot levels means that only two electrons and two holes can be resonantly photo-excited in the dot at any one time. If the time for which the dot is excited is much shorter than the relaxation time for electrons and holes in this level, then the dot can only absorb two electrons and two holes per laser pulse. Subsequent recombination will lead to the emission of two photons per laser pulse.

The absorption of a first electron-hole pair by a quantum dot, results in a small shift of the quantum dot transition energy due to the Coulomb interaction. This shift can be larger than the spectral linewidth of the exciting laser, thus preventing the absorption of a second electron-hole pair. In this case the quantum dot will absorb only one electron-hole pair per laser pulse, resulting in single photon emission from the dot.

It is also possible to limit the absorption of the dot to just one electron and one hole by polarising the exciting light. A circularly polarised laser will excite just one of the electron spin states, and one of the hole spin states. If the time for which the dot is excited is also shorter than time for either the electron or the hole to scatter to its other spin state, then the dot can absorb only one electron and one hole per laser pulse. In this case there will be one photon emitted per excitation pulse of the laser.

It is be possible to limit the emission from each quantum dot to single photons by filtering the polarisation of the emitted light. For example, using the polarisation splitter 31.

Some of the quantum dot transition energy lie very close in energy, allowing the excitation of two or more transitions at the same time. This can be used to generate N photons per laser excitation pulse. Another way to excite more than one transition per cycle is to use several excitation wavelengths.

The discrete energy spectrum of a quantum dot results in a relatively long lifetime for carriers in a particular level (i.e. relaxation time), because there are only a limited number of states into which the carrier can scatter. For instance, for an excited level in the quantum dot, the relaxation time to lower levels has been observed to be 10-100ps. The exciting laser pulse should be much narrower than the relaxation time, for instance the pulse could be 1ps wide, in order to avoid relaxation of the electron-hole pair excited in the dot followed by absorption of a second electron-hole pair. The lifetime of a carrier in a particular spin state has also been measured to be relatively long in a quantum dot.

It is also possible to tune the laser wavelength to be resonant with the bandgap transition of the quantum dot. In this case the exciting laser pulse must be shorter than the lifetime of the carriers in the ground state which is typically longer than that of the excited states and around 100ps-1ns. It is important to avoid collecting the exciting laser light by the fibre by using a non-colinear geometry for excitation and collection.

The maximum repetition rate of the laser (or equivalently minimum period) is limited by the time it takes the photo-excited electron and hole to recombine. Since this is typically 100ps-1ns, the maximum repetition rate is around 1-10 GHz. In practice one might want to use a lower repetition rate than this.

Figure 7 shows an arrangement for collecting single photons emitted from the single photon source 21. The source has a plurality of quantum dots. In such a source, each of the quantum dots will probably have slightly different transition energies due to variations in size between the dots. Therefore, although in this particular arrangement, many of the dots will emit single photons, each of the dots will emit photons at different energies. It is possible to select photons a particular energy (i.e. from when quantum dots) by using wavelength filter 60. Therefore, optical fibre 29 collects photons of all energies from single photon source 21 and feeds it into wavelength filter 60. The filter signal is then fed into polarisation splitter 31 as described with reference to Figure 2.

The arrangement of the pulsar diode 23, the polarisation filter 25 and the lens 27 are identical to those described with reference to Figure 2.

Figure 8 shows a photon source where photons emitted from a plurality of quantum dots 63. Except for the density of the quantum dot layer the structure is similar to that of figure 3. Therefore, to avoid unnecessary repetition like features are denoted by the same reference numerals. In the multiple quantum dot device, a quantum dot layer which has a higher areal density of dots is formed on an upper surface of the underlayer 33. The overlayer 37 is formed overlying the quantum dot layer 61.

In this type of structure, the emission from a large number of quantum dots (1 to 1000) can be collected. However, in this case, it is possible to extract the emission from a single quantum dot by spectrally filtering the emitted light.

In Figure 8, the core of the optical fibre 29 overlies a plurality of quantum dots 63.

Figure 9 shows a variation on the multiple quantum dot structure of Figure 8. Here, the underlayer 33, the dot layer 61 and the overlayer 37 are located within a cavity structure identical to the type described with reference to Figure 4. To avoid unnecessary repetition, like features are denoted with the same numerals.

Another advantage of the resonant cavity is that it will also act as a wavelength filter. This is because the resonance condition ($L_{cav} = \frac{m\lambda_{cav}}{2n_{cav}}$) is only satisfied for a narrow range of emission wavelengths. Thus, only these wavelengths are emitted into a narrow cone normal to the mirror 51, 52 as described with reference to Figure 4. The bandpass which can be thought of arising from the lifetime of the photon in the cavity, is largely determined by the reflectivity of the mirror 51, 53. Thus, increasing the reflectivities of the mirrors 51, 53 leads to a sharper cavity mode . The spectral bandpass of the cavity (or in other words, the width of the cavity mode) should ideally be designed to be roughly equal to the spectral width of the emitting quantum dot.

Figure 10 shows a schematic optical absorption spectrum of the plurality of quantum dots 63 shown in Figures 8 and 9. Absorption of the quantum dot is plotted along the y-axis (arbitrary units) photon wavelength of the emitted photons are plotted along the x-axis (arbitrary units). The optical spectrum of each quantum dot consists of a series of sharp lines whose width are determined by the homogenous broadening due to the finite lifetime. However, because of unavoidable fluctuations in the size and composition of the dots in a plurality of dots, the transition energies vary from dot to dot. Thus, the three absorption peaks 71, 73, and 75 are inhomogenously broadened.

If the quantum dots 63 are excited by a laser with a broad wavelength spectrum, a large number of quantum dots will be expected in the active region. However, because each of these emits a different wavelength, it is possible to filter the collected light in order to see the emission from a single dot. This is shown schematically in Figures 11a and 11b. Figure 11b shows a plot of emission intensity on the y-axis (arbitrary units) and photon wavelength on the x-axis (arbitrary units). Each of the plurality of spikes is due to emission from a particular transition within a single quantum dot. Figure 11b shows the results where filter 77 has filtered all but one of the photon wavelengths 79. Therefore, using pulsed excitation, it is possible to generate period emission of a single or multiple photons from a dot in a similar way to that described above. Preferably, the emitting area of the sample from which light is collected should contain a limited (<1000) number of optically active quantum dots.

Alternatively, a spectrally narrow laser may be used to excite a transition in just or a few quantum dots. Such a configuration is illustrated with reference to Figure 12. Figure 12 shows an optical absorption spectrum similar to that of Figure 10. Peaks 71, 73 and 75 are due to excitation of different quantum dot transitions. The incident laser wavelength 70 is much narrower here than the laser wavelength described with reference to Figure 10. Hence, the laser excites only a fraction of the quantum dot plurality: those with a transition energy equal to the laser energy. Hence, it can be seen that the emitted wavelength 72 is also much narrower than the emitted wavelength (before filtering) of

the spectrum shown in Figure 10. A laser of sufficiently narrow wavelength spectrum will excite just one of the quantum dots. Preferably, the emitting area of the sample from which light is collected should contain a limited (<1000) number of optically active quantum dots.

Figure 13 shows and electrically triggered quantum dot filter. The single photon source 21 is illuminated by a CW (continuous wave) laser with a narrow spectral line width 24. The CW laser 24 provides, as the name suggests, a continuous intensity and does not emit a pulsed signal. The wavelength of the CW laser is tuned to an optical transition energy of the quantum dot. The output from the CW laser is passed through a polarisation filter 25 and focused by lens 27 onto single photon source 21 as previously described with reference to Figure 2.

The single photon source 21 has an active region 81 which comprises a layer of quantum dots. These dots may be spatially distributed so that is possible to obtain emission from a single dot as described with reference to Figures 3 and 4, or they may be more densely packed so that a plurality of dots emit photons as described with reference to Figures 8 and 9. The quantum dot layer 81 is interposed between a top contact 83 and a bottom contact 85. The top and bottom contact 83 and 85 will typically be a p-contact and a n-contact. An AC voltage source 87 is then connected to top contact 83 and bottom contact 85 such that on application of an AC voltage, the field across the quantum dot layer 81 is varied. This periodic modulation varies the transition energies of the quantum dot.

The CW laser 24 is tuned to an optical transition of the quantum dot. It can be tuned to an excited transition or the ground state transition energy. The applied periodic modulation varies the transition energy of the dots. Therefore, the input radiation is only capable of exciting an electron or a hole into the relevant levels at a certain applied potentials to electrodes 83, 85. Hence, the period modulation of the voltage applied to electrodes 83 and 85 is equivalent to pulsing the laser radiation.

The applied periodic modulation should modulate the energies for quantum dot transition which is close to the resonance with the laser. Photon absorption can occur at times when quantum dot transition energy equals that of the laser, which occurs twice per period of the modulation. Subsequent recombination results in emission of photons. Photons are thereby emitted at time intervals determined by half the period of the applied modulation. For a stream of single photons at regular time intervals, it is important that the half period of the modulation be longer than the recombination time of the electron hole pair.

Figure 14 shows the single photon emitter 21 arranged in a resonant cavity of a type described with reference to Figures 4 and 9. To avoid unnecessary repetition, the underlayer 33, the quantum dot layer 35 and the overlayer 37 are identical to those described with reference to Figure 3. Also, the antireflection coating 43 and the optical fibre cable 29 are also identical described with reference to Figure 3.

The lower contact, which is a p^+ region acts as the lower mirror 51 of Figure 4. Upper contact 83 which is n^+ also functions is a partially reflecting mirror and are similar to mirror region 53 in Figure 4. The contact regions 85 and 83 which act as mirrors form a resonant cavity which has the same advantages as described with reference to Figure 4 and Figure 9.

Varying the applied voltage to the top contact 83 and the lower contact 85 varies the electric field across the quantum dot 47 due to the Stark-effect. The Stark-effect shifts the transition energies of the quantum dot. Other types of modulation can also be used such as periodic variations in the carrier density of the quantum dot or the carrier density of a surrounding layer or applied magnetic field, temperature, etc.

Figure 15 shows an absorption spectra of a single photon detected described with reference to Figures 13 and 14. Absorption is plotted on the y-axis (arbitrary units). Photon wavelength is plotted on the x-axis (arbitrary units). The laser wavelength 91 is

narrow and excites absorption at photon wavelengths 93, 95 and 97. Photons are emitted 99 at wavelength 97.

Figure 16 illustrates the relationship between single photon emission and applied AC perturbation in the device of Figures 13 and 14. In Figure 16a, applied AC perturbation on the y-axis (arbitrary units) is plotted against time on the x-axis (arbitrary units). In Figure 16b, the quantum dot transition wavelength (related to the quantum dot transition energy by $E=hc/\lambda$) is plotted on the y-axis and the elapsed time is plotted against the x-axis (arbitrary units). The time axis in both Figures 16a and 16b are identical. It can be seen, that a quantum dot transition wavelength varies periodically with that of the applied AC perturbation. The laser wavelength in this case (that is the applied radiation) is tuned to the transition energy of the quantum dot transition in the absence of any modulation. Photon absorption occurs at the times that the quantum dot transition energy equals that of the laser which occurs twice per period of the modulation. Subsequent recombination results in the emission of a photon. Photons are thereby emitted at time intervals determined by half the period of the applied modulation. For a regular stream of single photons it is important that the half period of the modulation be longer than the recombination time of the electron and hole.

The single photon emitter does not require excitation by illuminations. It is possible to introduce the electrons and the holes into the compliant energy levels for recombination by applied voltage. Figure 17 shows such an electrically operable device . The device comprises a buffer layer 103 formed overlying an upper surface of an injection gate 101. The buffer layer separates the injection gate 101 from an injection layer 105. Electrons can be induced in to injection layer 105. A tunnel barrier 107 is formed overlying an upper surface of injection layer 105. A quantum dot layer 109 is then formed overlying an upper surface of tunnel barrier 107. A p-type dopes barrier layer 113 is formed overlying an upper surface of an n-doped spacer layer 111 such that barrier layer 113 separated from the quantum dot layer 109 via spacer layer 111. The structure is finished with a cap layer 115 which overlies an upper surface of the doped barrier layer 113. Contacts are made to the dot layer 109 and the injection gate 101 such that the injection

gate 101 can be bias with respect to dot layer 109. In operation, the device is configured so that doped barrier layer 113 supplies holes to dot layer 109 so that the quantum dots are always populated by holes. Injection gate 101 can be biased with respect to dot layer 109 such that electrons are induced in injection layer 105. Electrons can be injected into the quantum dot layer 109 due to resonant tunnelling through tunnel barrier 107 by varying the bias between the injection gate and the hold house.

The injection of electrons into the dot layer 109 is regulated by applying a periodic voltage between the dot layer 109 and the injection gate 101.

The bias consists of a periodic stream of pulses between two levels V_{on} and V_{off}. The voltage level V_{off} is chosen so that the electron energy level in the injection level is lower than that in the quantum dot. This is shown in Figure 18. For clarity, the layers in Figure 18 have kept the same reference numerals as those in Figure 17.

The electrons in the electron injection layer 105 have an energy 121. In order to resonantly tunnel through barrier 107 into quantum dot layer 109, the electrons must have an energy equal to that of level 123 shown in the quantum dot. In the V_{off} state, the electrons do not have this energy. Therefore, no tunnelling can take place and hence, no recombination of electrons with holes in the dot can occur.

Figure 19, shows the state where the potential of the injection gate 101 is raised to V_{on}. Under these conditions, the band structure of the device changes so that energy level 121 in the electron injection layer 105 aligns with energy level 123 of the quantum dot and resonant tunnelling of a single electron can occur from injection layer 105 through tunnel layer 107 into quantum dot layer 109. Thus, recombination can occur and a photon can be emitted. It is clear, that as the tunnelling is controlled by switching the potential between V_{on} and V_{off}, the control of single photons can be achieved.

The electrically-pumped device can be arranged inside a resonant cavity in a similar manner to the optically pumped devices described above.

Figure 20 shows in detail a quantum dot emitter which is designed for emission at a wavelength of (λ) 1.3 μm which is suitable for long distance fibre optic transmissions.

The quantum dot layer 131 is sandwiched between an under layer 133 and an over layer 135. This groups of three layers (quantum dot layer, over layer and under layer) are in turn interposed between a resonant cavity structure such that light can be reflected within the cavity 137 which contains the said layers. The thickness of the cavity L_{cav} should be approximately given by the equation.

$$L_{cav} = \frac{m\lambda}{2n_{cav}}$$

where m is an integer and n_{cav} is the average refractive index of the cavity. For a GaAs cavity, λ at 1.3μm this leads to a cavity thickness L_{cav} of 190.9 nm for a $\lambda/2$ cavity (i.e. m = 1). The quantum dot layer 131 is positioned so as to lie at the antinode of the cavity mode. In this example, the antinode of the cavity lies close to the centre of the cavity. Possibly, there may be more than one quantum dot layer within the cavity and positioned close to an antinode of the cavity mode.

To define the cavity 137, layers 133 and 135 are imposed between Bragg mirrors 139 and 141. Each Bragg mirror 139, 141 comprises N (where N is an integer) repeats of two dielectric layers A and B. Dielectric layer A as a refractive index of n_a and a thickness of t_a. Dielectric layer B has a refractive index of n_b and a thickness of t_b. In Figure 20, each mirror comprises five periods of layers A and B. However, it should be noted that the two layers do not need to have the same number of layers. In order to form a Bragg mirror, the thickness of layers A and B are chosen so that $n_a t_a = n_b t_b = \lambda/4$. In this example the mirror is formed from alternating layer of AlAs ($n_a = 2.927$, $t_a = 111.04$nm) and GaAs ($n_b = 3.405$, $t_b = 95.46$nm). The number (=N) of repeats of layers A and B is chosen so as to obtain a suitable spectral bandpass for the cavity and should be sufficiently thick to effectively couple the cavity mode into the

numerical aperture of the optical fibre or cavity mode. In practice N should be chosen to be between 3 and 50.

Such a structure, using semiconductor Bragg mirrors, may conveniently be formed by epitaxial growth techniques such as MBE or MOCVD. For instance, a structure with AlAs/GaAs mirrors and InAs quantum dots (described below) may be grown on a GaAs substrate.

The layer structure consists of in sequence
a GaAs buffer layer, 143
20 repeats of (GaAs 95.46nm, AlAs 111.04nm), to form lower mirror 139
95.46 nm GaAs, to form under layer 133
a layer of quantum dots, 131
95.46 nm GaAs, to form over layer 135
20 repeats of (AlAs 111.04nm, GaAs 95.46nm) to form upper mirror 141.

The quantum dot layer can conveniently be formed from a 1.5-4 monolayer thick layer of InAs, which is known to self-assemble into nano-meter sized islands on the GaAs growth surface during MBE or MOCVD growth. Overgrowth of these islands with GaAs or AlGaAs leads to the formation of a layer of quantum dots. The growth parameters should be optimised to produce quantum dot transitions at the desired wavelength – in this case 1.3 microns. We have found for MBE growth, it is best to grow the quantum dot layer with a substrate temperature of 500-530°C and with a relatively low Indium flux rate so as to achieve a growth rate for InAs of around 0.01 microns/hour. The areal density of quantum dots can be varied by controlling the thickness of InAs deposited.

This method can also be used to form multiple layers of quantum dots within the cavity, which can be separated by GaAs or AlGaAs barriers.

The structure may be etched using standard photolithography so as to form mesas with a diameter between 0.5 and 500 microns. Preferably the mesa may have a diameter so as to support a single transverse mode inside the cavity. The mesas may be etched into the upper mirror or upper mirror and cavity layer. It may also extend into the lower mirror.

The optical fibre or collection optic (29 from Figure 2) may be placed on the substrate side 145 of the wafer, or alternatively, on the top side 147. Optionally, an area of the substrate 143 may be etched away, so as to allow a more efficient coupling to an optical fibre and convenient mounting of the fibre 29. An etch stop layer may be included in the epitaxial growth, to allow the depth of the substrate etch to be carefully controlled. An anti-reflection coating may be deposited of the collection face to reduce the Fresnel losses.

In this example the bulk of the cavity is made of GaAs 133, 135, however, the cavity could also be formed from an AlGaAs layer. In this case the thickness of the cavity must be adjusted so as to maintain resonance of the cavity mode and the quantum dot, because of the difference in the AlGaAs and GaAs refractive indices.

One or both of the Bragg mirrors 141,139 can be formed using alternating layers of dielectrics such as SiO_2 and TiO_2. For the lower mirror the substrate can be etched away before the lower Bragg mirror is deposited. An etch stop layer may be included in the growth structure to allow this.

Figure 21 shows a variation of the structure of Figure 20. Here, one of the mirrors 141 of the cavity has been formed using a metal layer 151. A metal of high reflectivity may be chosen such as gold. The example of a cavity resonant with a wavelength of 1.3μm is again given. In this case we chose a λ cavity (i.e. m = 2) of GaAs, requiring $L_{cav} \sim 381.84$nm. The cavity could alternatively comprise AlGaAs.

In this example the mirror reflectivities are different and thus the cavity mode is not symmetric about the centre plane of the cavity. This means that the antinode of the

cavity mode lies away from the centre of the cavity. For maximum coupling the quantum dot layer 131 should be shifted to lie at the antinode of the cavity 137.

The structure includes a so-called phase-matching layer 153 between the cavity 137 and the metal mirror 151, which compensates for the fact that the cavity mode does not have an antinode at the edge of the metal 151. For this cavity, the phase matching layer may be formed from a GaAs layer which is approximately 70 nm thick.

The layers may again be grown by MBE or MOCVD on a GaAs substrate. The layers comprise
a GaAs buffer layer, 143
10 repeats of (GaAs 95.46nm, AlAs 111.04nm), 139
193.3 nm GaAs, 133
a layer of quantum dots, 131
188.54 nm GaAs, 135
70 nm GaAs (phase matching layer 153).
The quantum dots are formed in the way described with reference to Figure 20.

A 200nm gold layer is evaporated on the top surface to act as the top mirror 15.

The structure may be etched using standard photolithography so as to form mesas with a diameter between 0.5 and 500 microns. This can conveniently be done by first patterning the metal 151, and then using this metal pattern as a template for etching the semiconductor. The mesas may be etched into the upper mirror 151 and cavity layer 153. It may also extend into the lower mirror 139. Preferably the mesa may have a diameter so as to support a single transverse mode inside the cavity 137.

The optical fibre 29 or collection optic is placed on the substrate side 145 of the wafer. An area of the substrate may be etched away, so as to allow a more efficient coupling to an optical fibre and convenient mounting of the fibre. An etch stop layer may be included in the epitaxial growth, to allow the depth of the substrate etch to be carefully

controlled. An anti-reflection coating may be deposited on the collection face to reduce the Fresnel losses.

In this example the bulk of the cavity 137 is made of GaAs, however, the cavity could also be formed from an AlGaAs layer. In this case the thickness of the cavity must be adjusted so as to maintain resonance of the cavity mode and the quantum dot, because of the difference in the AlGaAs and GaAs refractive indices.

The lower Bragg mirrors could be formed using alternating layers of dielectrics such as SiO_2 and TiO_2. For the lower mirror the substrate can be etched away before the lower Bragg mirror is deposited. An etch stop layer may be included in the growth structure to allow this.

CLAIMS:

1. A photon source configured to allow emission of a predetermined number of photons at predetermined times comprising:

a quantum dot having a first confined energy level capable of being populated with a first carrier which is an electron and a second confined energy level capable of being populated by a second carrier which is a hole; and

supply means for supplying carriers to the said energy levels, wherein the supply means comprises pulsed incident radiation configured to resonantly excite a predetermined number of carriers into the first and second energy levels respectively to allow recombination of carriers in said quantum dot to emit at least one photon;

and wherein said quantum dot is encapsulated between two layers having different lattice constant to the quantum dot.

2. A photon source according to claim 1, wherein the pulse has a duration which is less than the relaxation time of a carrier which it excites in the quantum dot.

3. A photon source according to either of claims 1 or 2, wherein the time between leading edges of successive pulses is greater than the recombination time of and electron and hole in the quantum dot.

4. A photon source according to any preceding claim, wherein the said incident radiation has a predetermined polarisation.

5. A photon source configured to allow emission of a predetermined number of photons at predetermined times comprising:

a quantum dot having a first confined energy level capable of being populated with a first carrier which is an electron and a second confined energy level capable of being populated by a second carrier which is a hole; and

supply means comprising incident radiation for supplying carriers to the said energy levels, and modulation means configured to vary the transition energy of the quantum dot,

wherein the supply means are configured to supply carriers to at least one of the energy levels to allow recombination of carriers in said quantum dot to emit at least one photon.

6. A photon source according to claim 5, wherein the modulation means comprises an AC voltage applied to vary the electric field across said dot.

7. A photon source according to either of claims 5 or 6, wherein the modulation means comprise means to vary the carrier density within the source.

8. A photon source according to any of claims 5 to 7, wherein the modulation means comprises means to vary a magnetic field applied to the said quantum dot.

9. A photon source according to any preceding claim, comprising:

a plurality of quantum dots having first confined energy levels capable of being populated with first carriers which are electrons and second confined energy levels capable of being populated by second carriers which are holes, the quantum dots having a distribution of sizes such that the level of the first confined energy levels and/or the second confined energy levels differs between quantum dots;

and a filter configured to select photons of a particular energy emitted from one quantum dot.

10. A photon source according to any preceding claim, comprising:

a plurality of quantum dots having first confined energy levels capable of being populated with first carriers which are electrons and second confined energy levels capable of being populated by second carriers which are holes, the quantum dots having a distribution of sizes such that the level of the first confined energy levels and/or the second confined energy levels differs between quantum dots,

wherein the supply means are configured to selectively inject carriers of a predetermined energy into one of the energy levels of one quantum dot to allow recombination of a predetermined number of carriers in said quantum dot to emit at least one photon.

11. A photon source according to any of claims 1 to 8, comprising a plurality of quantum dots.

12. A photon source according to any preceding claim, wherein the supply means are configured to repetitively supply a single carrier to the at least one energy level to allow emission of a single photon separated from each other by predetermined time intervals.

13. A photon source according to any preceding claim, wherein the source has an output surface through which the emitted photons are collected, the source further comprising coupling means for coupling the emitted photons to a fibre optic cable.

14. A photon source according to any preceding claim, wherein the source has an output surface through which the emitted photons are collected and comprises an anti-reflection coating located on said output surface.

15. A photon source according to any preceding claim, wherein the source further comprises a lens for collecting emitted photons.

16. A photon source according to any preceding claim, wherein the source comprises a mirror cavity having a mirror located on opposing sides of said quantum dot.

17. A photon source according to claim 16, wherein the source has an output surface through which the emitted photons are collected and said mirror closest to said output surface is partially reflective such that it can transmit the emitted photons.

18. A photon source according to either of claims 16 or 17, wherein the energy of the cavity mode for said mirror cavity is substantially equal to that of the emitted photons.

19. A photon source according to any of claims 16 to 18, wherein the distance between the two mirrors L_{cav} bounding the cavity is defined by the equation:

$$L_{cav} = \frac{m\lambda}{2n_{cav}};$$

where λ is the wavelength of the emitted photons,
m is an integer and n_{cav} is the refractive index of the cavity.

20. A photon source according to any of claims 16 to 19, wherein the spectral band-pass of the cavity is substantially equal to the spectral width of the radiation emitted from the dot in the absence of a cavity.

21. A photon source according to any claims 16 to 20, wherein the quantum dot is positioned at an anti-node of the standing wave pattern caused by said mirrors.

22. A photon source according to any of claims 16 to 21, wherein at least one of the mirrors is a Bragg mirror comprising a plurality of alternating layers wherein each layer satisfies the relation

$$nt = \frac{\lambda}{4}$$

wherein λ is the wavelength of the emitted photons, n and t are the refractive index and thickness respectively of a layer within the mirror.

23. A photon source according to any of claims 16 to 22, wherein a mirror comprises a metal layer and a phase matching layer.

24. A photon source according to any preceding claim, wherein the source further comprises an optic fibre cable for collecting the emitted light.

25. A photon source according to claim 24 when dependent on claim 16, wherein the wavelength of operation of the fibre optic cable is substantially equally to the wavelength of the cavity mode.

26. A photon source according to either of claims 24 or 25, wherein the optical fibre has a non-reflective coating.

27. A photon source according to any preceding claim, wherein the source further comprises a polariser configured to select emitted photons of a particular polarisation.

28. A photon source according to any preceding claim, further comprising filter means configured to transmit photons having a particular energy.

29. A method of fabricating a photon source configured to allow emission of a predetermined number of photons at predetermined times, the method comprising the steps of:

forming a quantum dot layer by growing a layer of a first material on a second material, wherein there is a variation in the lattice constants between the first material and the second material, the first material being deposited in a layer of a thickness to form a quantum dot, forming a layer of a third material overlying the first material such that the quantum dot is encapsulated between the first and third materials, said quantum dot having a first confined energy level capable of being populated with a first carrier which is an electron and a second confined energy level, capable of being populated by a second carrier which is a hole,

the method further comprising the step of providing means to supply pulsed incident radiation supply means for resonantly supplying carriers to the said energy levels, wherein the supply means are configured to supply a predetermined number of carriers to at least one of the energy levels in the quantum dot to allow recombination of a predetermined number of carriers in said quantum dot to emit at least one photon.

30. A method of fabricating a photon source configured to allow emission of a predetermined number of photons at predetermined times, the method comprising the steps of:

forming a quantum dot layer by growing a layer of a first material on a second material, wherein there is a variation in the lattice constants between the first material

and the second material, the first material being deposited in a layer of a thickness to form a quantum dot, forming a layer of a third material overlying the first material such that the quantum dots are encapsulated between the first and third materials, said quantum dot having a first confined energy level capable of being populated with a first carrier which is an electron and a second confined energy level, capable of being populated by a second carrier which is a hole,

the method further comprising the step of providing supply means for supplying carriers to the said energy levels, the supply means comprising means to supply incident radiation and modulation means configured to vary the transition energy of the quantum dot, the supply means being configured to supply carriers to at least one of the energy levels in the quantum dots to allow recombination of carriers in said quantum dot to emit at least one photon.

31. A photon source as substantially hereinbefore described with reference to any of figures 1 to 21.

32. A method of fabricating a photon source as substantially hereinbefore described with reference to any of figures 1 to 21.

INVESTOR IN PEOPLE

Application No:	GB 0224125.5	**Examiner:**	Martyn Dixon
Claims searched:	1,29 and appendant claims	**Date of search:**	5 November 2002

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Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): H1K (KELQ,KELX,KEAA,KEAX,KFXL)

Int Cl (Ed.7): H01L; H01S

Other: Online: EPODOC,WPI,JAPIO,INSPEC,IEL,APL

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	Gerard *et al*, J. Lightwave Technology, vol 17, no 11, November 1999, pages 2089-2095, "Strong Purcell Effect for InAs Quantum Boxes in Three-Dimensional Solid-State Microcavities"	
A	Molotov *et al*, JETP Letters, vol 63, no 8, April 1996, pages 687-693, "Quantum cryptography based on quantum dots"	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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